Eksig 2023

"From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research"

Proceedings

MILANO

19.06 — 20.06

2023 eksig
DRS special interest group on experiential knowledge

Design Research Society

POLITECNICO MILANO 1863
DIPARTIMENTO DI DESIGN

International Conference 2023 of the Design Research Society Special Interest Group on Experiential Knowledge (EKSIG)

Conference Proceedings

From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research

19-20 June 2023
Department of Design, Politecnico di Milano, Italy

Editors: Silvia Ferraris, Valentina Rognoli, Nithikul Nimkulrat

Published 2023 by
Politecnico di MIlano
ISBN: 9788894167436

2023 eksig DRS special interest group on experiential knowledge

Design Research Society DRS

POLITECNICO MILANO 1863 DIPARTIMENTO DI DESIGN

Table of Content

Conference theme

Prototype and prototyping play a key role in experiential knowledge since they support the interconnections and collaboration among researchers and practitioners in many design fields. The role of prototypes in design research is characterised mainly by the general function of representing ideas and giving intelligible form to undetermined and abstract concepts pertaining to design solutions. Such a principle of transition from vagueness to clarity illustrates views on the role of prototypes which dot the diverse landscape of design research. Indeed, the evolution of design research in the past twenty years has led the path to a wide range of new possible prototypes applications.

Originally, in the industrial context, prototypes were made to test, evaluate, and improve the product until the final design and production phase. When design became an academic discipline, the scope of its enquiry expanded, embracing new areas of interest (i.e., sustainable design, materials design, participatory design, service design, user experience design, etc.), and their methodologies and scopes. During this evolution, the role that prototypes play in design research started to be questioned.

Indeed, nowadays, the role of the prototype encompasses several possibilities that link to the context and aim of the design research. When a general aim of the investigation is to develop a new design solution and make it *real* and available to users at the end of the process, prototypes support the transition from the idea to the final product. In this realm, prototypes play a crucial role, as they visualise, validate, experiment, and create such new solutions. Interestingly, prototypes for this kind of design research can be simple paper models that anticipate interactions up to complete *working* prototypes that are very close to the final product. In the digital field, provisional solutions are released on the market and updated afterwards. Prototypes, in this case, merge with the *final* products. New boundaries are broken between a final design and what is not.

Furthermore, the products that designers call to envision are becoming more and more complex. They are equipped with sensors, processors, and connected devices that support the interaction with digital interfaces, applications, and complex services. Hence, prototypes are meant to support design processes that rely on the supplementation of new kinds of expertise – such as user experience design, interaction design, material design and computer science – besides those traditionally integrated – such as product design, mechanical and electronic engineering). In this regard, the prototype embodies the translation of different design languages into a developing concept. Moreover, design research that explores and discusses possibilities might go beyond the development of concrete solutions and tackle significant issues (i.e., the impact of technology on society; climate change, social innovation) to reach new understating and develop new knowledge. This kind of design research usually occurs in academia and requires exploratory and speculative studies. Some of this design research is about tangible objects or is based on material experimentations. Typically, prototypes play an important role in the first explorative phases, in this realm since they enable the transition *from abstract to concrete* through immediate and factual experience. Designers research by envisioning solutions, imagining possible futures, exploring new fields, and feeding the design discourse with emerging contemporary issues and fictional scenarios.

Overall, the multifaceted landscape of today's design research opens to a wide range of meanings that define what a prototype is and does. The discussion on prototypes' identity is open. Instead of seeking to find an ultimate definition of prototype and its role in today's design research, the conference aims at eliciting a conversation around the current and multiform panorama of experimentations around and with prototypes.

The call for paper encourages contributions with the following:

- What are the new roles of prototypes in these evolutionary pathways in design research?
- How do new sophisticated, integrated, and advanced prototypes support research in various areas of design?
- How do different research contexts (practice, R&D, and academia) collaborate in design research due to the making and use of prototypes?
- How do prototypes enable the creation of theoretical knowledge and support speculative research?
- How do prototypes enable the creation of practical knowledge and support empirical research?
- How do prototypes enable the exploration of new research fields?

Organisation

Programme Committee

Silvia D. Ferraris, Politecnico di Milano, Italy

Valentina Rognoli, Politecnico di Milano, Italy

Nithikul Nimkulrat, OCAD University, Canada

Camilla Groth, University of South-Eastern Norway

Scientific Committee

Camilla Groth, University of South-Eastern, Norway

Carla Langella, University of Naples Federico II, Italy

Eujin Pei, Brunel University London, United Kindom

Louise Valentine, The Design Journal, United Kindom

Lucia Rampino, Politecnico di Milano, Italy

Manuela Celi, Politecnico di Milano, Italy

Nithikul Nimkulrat, OCAD University, Canada

Owain Pedgley, METU, Turkey

Silvia D. Ferraris, Politecnico di Milano, Italy

Valentina Rognoli, Politecnico di Milano, Italy

Venere Ferraro, Politecnico di Milano, Italy

Martínez Torán Manuel, Universitat Politècnica de València, Spain

Youn-kyung Lim, KAIST, Republic of Korea

Jouke Verlinden, University of Antwerp, Belgium

Organising Committee

Francesca Mattioli, Politecnico di Milano, Italy

Caterina Dastoli, Politecnico di Milano, Italy

Sofia Soledad Duarte Poblete, Politecnico di Milano, Italy

Alessia Romani, Politecnico di Milano, Italy

Francesco Leoni, Politecnico di Milano, Italy

Keynotes

Prototypes: Footholds to the future and footsteps from the future?

Pieter Jan Stappers – TU Delft, Netherlands

Prototyping is a core activity of design, and a large part of the contribution that design actions can make to the quest for new knowledge. In that quest it provides tangible points where the abstract (theory) meets the concrete (‘real' world) on which we can base future steps: footholds. On the other sides prototypes may realize concrete experiences with as yet inexistent situations: they allow us to observe and collect data from a phenomenon that before the prototype was only speculation: footsteps.

As a part of industrial production, the term prototype has been around for about a century, in design research it has become prominent in the discourse for a few decades. And the term has functions in other disciplines too, as in psychology and philosophy.

There are several areas worth addressing:

- We should take care of both the noun prototype and the verb prototyping. They are not the same, even though in academic shorthand they are used interchangeably in sentences.
- How does prototyping relate to the core competencies of doing design: what is ‘design' about them?
- Engineering, psychology, and industrial practice use the term differently? Can those differences inspire us to better understand what we are doing ourselves?
- How do we prototype the larger intangible outcomes of design, when design is addressing services, and global issues as sustainability, and the ‘artefact in the museum' tells less about either the knowledge that it carries or the impact it may foretell.

Pieter Jan Stappers is professor of Design Techniques at Delft University, Faculty of Industrial Design Engineering. His research and teaching focus on the connections between research and design, such as techniques for user participation (codesign and context mapping), and the role of doing design as a part of doing research (research through design). Key terms include perception, creativity, visualization, empathy, systems thinking, and prototyping.

Prototyping In Practice: for Research and Beyond

Kathryn Marinaro – Argodesign, Creative Director

Prototypes are useful beyond usability testing; they're a strategic tool to drive alignment, to communicate value and vision, and to get digital products built correctly in a more efficient manner. They help teams move quickly by making instead of swirling in ideas. Through her work at IBM and currently as a Creative Director at the digital product design agency, argodesign, Kathryn Marinaro has found that the best practical uses for prototypes are for qualitative and strategic purposes.

In this keynote, Kathryn will share her experience creating and utilizing prototypes to generate ideas with subject matter experts, to understand resonance and value with end-users, to explore new interaction models for emerging technology, and to communicate visions to stakeholders who control the direction of a product. She'll share examples of prototypes used throughout the process of the programs she leads and their outcomes and impact. Prototypes aren't just for testing, they're for delivering value.

Kathryn Marinaro is an award-winning Creative Director who envisions the future and develops products and strategies for a wide variety of clients at argodesign. She is the author of Prototyping for Designers, published by O'Reilly, and has employed user-centered methodologies to create and iterate on impactful experiences in health wearables, AI interaction patterns, AI image recognition and training interfaces, and cloud development tools, while working on world-class design teams like IBM Watson Visioneering and IBM Mobile Innovation Lab. She has gained recognition as one of Austin's Top 50 Female UX Designers and as part of the Advisory Board for the inaugural Austin Design Week. She's been featured in articles in Fast Company, Time Out New York, Architect Magazine, ArtInfo, Make Magazine, and the Visual Arts Journal.

Advanced materials promoting sustainable practices

Aldo Sollazzo – Noumena, Founder and CEO

In this keynote address, Aldo Sollazzo, CEO of Pure.Tech, will delve into the crucial role of advanced materials in combating climate change and their potential to revolutionize various industries. The lecture will explore how Pure.Tech's innovative materials offer a novel concept of ecology, enabling sustainable solutions across sectors such as construction, fashion, packaging, and more. Sollazzo will discuss the urgent need to address climate change and highlight the impact of greenhouse gas emissions on our environment. He will showcase how advanced materials developed by Pure.Tech can effectively mitigate these challenges by reducing carbon footprints, improving air quality, and promoting sustainable practices. Notably, Sollazzo will highlight that implementation of the Pure.Tech in several projects world wide. These include the Spanish Pavilion 'Intelligent Forest' at Dubai Expo 2020, the world's first 3D printed retail store for sneakers by 'Presented by' in Dubai and Riyadh, BAFTA theater in London, and as well Pure.Ceiling a module false ceiling system for the interiors of commercial offices and retails spaces. Currently, Pure.Tech is also collaborating with several fashion brands across the world, actively developing various applications for the textile and fashion industry to promote sustainability and reduce environmental impact.

Aldo Sollazzo is an Italian entrepreneur and innovator, expert in robotics, computer vision, and computational design. He is the CEO of Noumena since 2011, a data-driven company implementing computer vision and machine learning to study and analyze spatial dynamics. As part of the Noumena Group, he is also the director of Reshape, a platform focused on the industrial application of material-driven sustainable technologies, and of LAMÁQUINA, a large-scale 3D printing factory, shaping new architectural solutions integrating advanced manufacturing and computation. At the Institute for Advanced Architecture of Catalunya in Barcelona, he is the Director of the Master in Robotics and Advanced Construction. In 2019 Aldo received, from the Italian President of the Republic, the title of Knight of the Order of the Star of Italy for the promotion of national prestige abroad as a recognition of his scientific and technological activities. Aldo has made many appearances as a guest speaker at Conferences and University Seminars, amongst them European Conference on Computer Vision, Barcelona Urban Tech, Future City Summit, The Venice Biennale and TEDx Barcelona.

Paper index

Hiperlinks to full papers

Track 1 Interaction, Data and AI / 1

Track 2 Service Design and Policymaking

Track 3 Research processes and methods / 1

Track 4 Sustainable and Biological solutions

Track 5 Materials and Crafts

Track 8 Education processes and methods

To Prototype to Learn Fronting Uncertainties. A Pedagogy Based on Anti-Disciplinarity, Thinkering and Speculation
Guida, Francesco E.
Prototypes, translation and research in social design education
Mattozzi, Alvise; Ventura, Jonathan
Prototyping of theories
Schaldemose, Sisse
Role of Physical mock-ups in the Ideation phase: a thematic analysis of the Pedagogic approach
T N, Subramanya; B K, Chakravarthy; Joshi, Purba; Singh, Akanksha
From Prototype1.0 to Prototype3.0: Situated learning in Prototype design for Chinese labour education
Yang, Linlin; Zhang, Shangjie; Meng, Danqing; Lu, Ziwen; Fan, Fei

Track 9 Research processes and methods / 2

Origins of design choices: retrospective analysis of the resulting prototype of a Research through Design project
Mertens, Audrey; Yönder, Çiğdem; Hamarat, Yaprak; Elsen, Catherine
What is Your (Freaking) Problem? Prototypes for problem exploration on early stages of design
Ruiz, Juan; Wever, Renee
Process as prototype: exploring complex knowledge exchange in the production of low-cost buoyancy aids in Zanzibar through the participatory design of a 'workflow system'
Shercliff, Emma; Devall, Lucy; Conrad, Franziska
The prototype-evaluation choreography
van Zeeland, Eveline

Track 10 Mobility and Transportation

The social role of a motorcycle prototype in fostering collaboration in a self-guided team of students
Amadeo, Azul; Mattioli, Francesca
Proto-flighting in the wild: a creative technologist approach to drone prototyping
Cleveland, Peter; Joseph, Frances
DIY Bus: Exploring Boundary Objects in Participatory Design Research
Dhaundiyal, Dhriti; Sharma, Nishant

Using machine learning as a material to generate and refine aircraft design prototypes
Tan, Linus; Luke, Thom; Di Pietro, Adriano; Kocsis, Anita

Track 11 Interaction, Data and AI / 2

The eloquent void: strangeness in data physicalization about loneliness
Guedes Mesquita, Rebeca; Thoring, Katja

The Artificial lyricist: Prototyping an Interactive Opera for Humans and Machines
Mattias Rylander, Hedvig Jalhed, Kristoffer Åberg

Graft-games: Experiential prototyping for the exploration of crossovers between craft and gaming
Potter, Gemma May

Idiotic Agents: Exploring more open-ended and creative interactions between humans and Intelligent Personal Assistants in the home
Tsilogianni, Maria

Track 12 Fiction & Speculative design

Crafting e-waste through speculative narratives to raise material awareness
Burzio, Giorgia; Ferraro, Venere

Think with your hands: Exploring the Future via Prototyping
Gumus Ciftci, Hazal; Plymire, Konnor

Prototyping Dialogues
Ravnløkke, Louise; Binder, Thomas

Design Fiction Prototyping to tackle Societal Challenges
And support Design for Sustainable Behaviours
Stepanovic, Mila

Materialization of the Future: The Demarcation Line between Prototypes and Demonstrators
Sviridova, Aleksandra; Verlinden, Jouke Casper

Track 1: Interaction, Data and AI 1

- Data Drawing and Data Tinkering

- Prototyping as making sense of expressions

- Documenting End User Needs in an Interactive Virtual Reality Prototyping Environment for a VR-PD Approach in Architecture

- New patterns of prototyping: developing concepts with playful exploration and probing. A case study within arts and design

- Bee Buzz Buddy: An Interactive Digital Toy to Facilitate Tangible Embedded and Embodied Interactions for Young Children’s Active Play

Data Drawing and Data Tinkering

Ayşe Özge Ağça, University of Southern Denmark
Jacob Buur, University of Southern Denmark

Abstract

Data visualizations and data physicalizations have become popular methods of making big data accessible to non-specialists and uncovering hidden rationales. This pictorial suggests how the acts of data drawing and data tinkering can engage young people in understanding their own data. We asked graduate design students to track their water consumption and waste recycling through drawing and prototyping. We analysed 32 data drawings and 30 data tinkerings using Gestalt Principles and the Theory of Affordance. Through our analysis, we generate a set of ‘data-gestalt’ nouns and ‘data-affordance’ adjectives, which help explain how our collaborators are able to ‘engage’ experientially with data; how abstract data is given intelligible form. By listening to how they talk, we realise that these concrete ways of engaging provide ownership of ‘data work’ and enhance awareness of (un)sustainable consumption behaviours. We argue that data drawing and data tinkering may have a potential to influence consumption habits.

Consumption behaviour; Data Engagement; Hand-drawing; Prototyping; Affordance

Recently, promising suggestions have been published in the interaction design community for engaging a broader audience relating to digital data. The Dear Data project (Lupi and Posavec 2016) showed highly unconventional but very human visualisations of self-tracking data. Two graphic designers communicated hand-drawn notations via postcards between London and New York. They counted, for instance, how many doors they passed in a week, how many complaints they heard, and how often they laughed – in compelling visual diagrams.

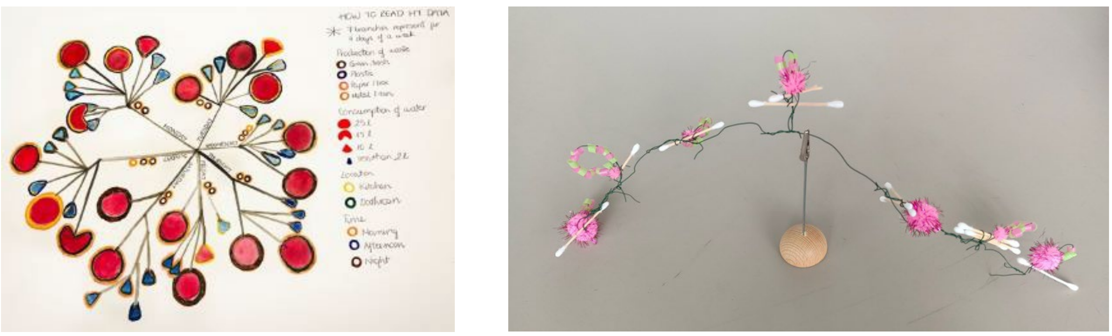


Figure 1. Examples of a data drawing (left) and a data tinkering (right) of weekly water consumption

Within business anthropology, Anderson et al. (2009) have shown how people’s digital data may be visualised in a way where people themselves can reflect on their practices and explain what the data mean. Human rights advocates and activists have argued for the importance of data visualization techniques to influence and convince people about action plans (Pandey et al. 2014), and researchers have tried to prove an effect of interactive data products (Laschke et al. 2011). Data physicalization was proposed as a way of shifting data visualisation into 3D space (Dragicevic et al. 2019), with a richness of examples from ancient times to the present-day digitally fabricated contraptions. Such physicalizations lend themselves to engaging 'ordinary people' in taking ownership and making sense of their own data (Buur et al. 2018, Buur et al. 2021). Based in Object Theatre, Karyda et al. (2020) have pushed even further in devising 'Data Objects' that prototype digital self-tracking data.

This paper describes an experimental investigation to develop 'data drawing' and 'data tinkering' methods (Figure 1) to support people in experiencing their own data about consumption. We hope to challenge our collaborators to reflect on their own practices and ultimately provide incentives towards more sustainable habits. We encouraged 40 graduate design students to visualize their own water consumption and waste recycling. After comparing and discussing their notations, we challenged the cohort to tinker data physicalizations with tangible materials. In the following, we analyse the results to understand better what it means to 'draw' and to 'tinker' data and what experiential knowledge it elicits. By drawing on Gestalt Principles and the Theory of Affordance in the analysis, we boldly suggest that such terms as 'data-gestalt' and 'data-affordance' may help us prototype 'engaging' data.

Methods we used

To investigate how young people may engage with data about their own consumption, we challenged our two studios of each 20 designers to record their individual use of water and their recycling of waste for a one-week period. We are particularly interested in how young people engage with data, because we want to understand their opinions about behaviour change for further studies. GSDR 2019 (The Global Sustainable Development Report) shows that young people are key agents of sustainable behavioural change. As we can see from the \`Friday for Future´ movement (2018) and the SDG´s (Sustainable Development Goals) \`Bringing Data to Life´ stories (2022), young people are eager to look for solutions to current and future environmental problems.

We asked the designers to visualize the data using hand-drawn techniques with inspiration from the Dear Data project (Lupi and Posavec 2016). The two studios produced a total of 32 data drawings, which we co-analysed with the participants at the whiteboard using Dimensional Analysis (Kools et al. 1996) and Affinity Diagramming (Kawakita 1982).

As dimensions, we provokingly asked, for instance, "Who uses most water? Which drawing has most detail? Which drawing explains most clearly? Which drawing is most abstract? Which drawing is most beautiful? ..." The dimensional analyses enabled the participants to compare each other's approaches to data drawing. While some drawings took longer to understand, others were easier as they built on well-known visual cues. We recorded the analysis sessions on video to understand how participants talked about their consumption data and how they related to their data drawings (Figure 2, left). Following the co-analysis, we got curious about how to conceptualize the clustering. Here, we took inspiration from Gestalt Principles (Ellis 1999, Koffka 1963). We realised that one may recognise data patterns not just conventionally in tables and graphs but also in tallies, circles, units, symbols, and concepts.

As a second step in the session, we set up a table with prototyping material, like foam, string, plastic cups, pearls, marbles, and all kinds of bric-a-brac. We provided the participants with a standard set of consumption data from one family (Table 1) and challenged them to build physical objects expressing the data in a 1-hour session. The two studios produced a total of 30 data tinkerings. After they each explained their data tinkering, we engaged the participants in co-analysis and recorded how they talked about their prototypes, Figure 2 (right).

Table 1. Data set of one family's water consumption for a week used for data tinkering.

Activity in liters	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Shower / Dishwashing	135	100	140	125	90	55	200
Drinking	1	4	2	1.5	1	0.7	1
Flushing	12	24	15	12	30	35	32

When following up on the co-analysis, we realised that the Theory of Affordance (Gibson 1979, Norman 2013) can help. We were curious to see which 'data-affordances' might emerge: What did participants expect one might do with their data physicalizations? What acts might they afford? We grouped the constructs according to what materials and shapes mean and invite us to do, as expressed by the designers themselves in their narratives and body actions while presenting.

In the following chapter, we will recap the theories of gestalt and affordances and show the resulting clusterings of data-gestalt and data-affordances. Then we will investigate how the comparisons of data drawings and data tinkerings elicited conversations among the participants about their own consumption, and how they might change habits. In a final chapter we will discuss how the concepts of data-gestalt and data-affordance may inspire design.

Drawing data-gestalt

Information visualisation is a core technique for visual representation of abstract data to aid cognition for participants of different disciplines (Ellis 1999, Evergreen and Metzner 2013). Ware suggests that data visualisation supports external cognition and humans' visual ability to identify patterns, as expressed in the common saying: "I see what you mean!" (Ellis 1999). Koffka´s Gestalt Principles help us understand the relation between the meaning of data and seeing the data. The principles were established by a group of German psychologists. The word 'Gestalt' simply means patterns and Koffka discusses quantity, order and meaning (Koffka 1963, Norman 2013). Wertheimer talks about Prägnanz (Group making) as a main principle to predict the interpretation of sensation (Ellis 1999). He explains that the principles easily translate into a set of basic design principles such as proximity, similarity, connectedness, continuity, relative size, and common fate (Ellis 1999).

Figure 2. The co-analysis of data drawings (left) and data tinkerings (right)

While these principles can be valid on their own, they are used in intricate combinations to create a semantic whole.

Gestalt Theory is expressed in 'laws': The Law of Proximity says that things that are close together are perceptually grouped. They form patterns, and the individual patterns can also determine how they are grouped in the Law of Similarity. The Law of Connectedness tells how graphical grouping is substantiated by lines and proximity, shape, colour, and relative size. The Law of Common Fate states that objects working or moving in the same direction appear to belong together. The Law of Relative Size explains how two or more objects can have meaningful size relations from the human retina perspective (Ellis 1999, Koffka 1963, Ware 2012). Gestalt Theory may help us understand how the participants express and perceive abstract data in their drawings. Gestalt psychologists state that the semantic value of something is as easy to perceive as its colour. However, perception is not only based on sensibility. It needs to be equipped with meaning. When we define such meanings with principles, we begin to form certain patterns. These patterns trigger our cognitive visualisation process. Djajadiningrat et al. (2002) discuss how the semantic approach can inform interaction design. Cognition, knowledge, and past experiences influence how tangible objects communicate through symbols and signs. In this way, people may see data and create meaning in interaction design.

According to Dragicevic et al. (2019) there are three main motivations for creating visualisations: to discover, to present and to enjoy. In the Dear Data project, we can see all three motivations play into the hand drawings to increase engagement with mundane, daily data (Lupi and Posavec 2016). When trying to make sense of such mundane experiences, people express experiential knowledge in narrative form (Storkerson 2009). To understand how the act of drawing data motivates participants to scrutinize their water consumption and recycling behaviours, we look for repetitive patterns in their visualizations with the help of Gestalt Principles.

What participants draw as 'data-gestalt'

We identify seven 'data-gestalt' patterns that we express in nouns on the next page (Figure 3). Our point is that people, when challenged with drawing data, perceive a variety of patterns. Through the analysis, we realized that the data-gestalt patterns also tend to support specific actions like counting, tabulating, coding, as noted in the hand-written notes. The group we named 'Concepts' combines drawings that are more abstract or complex. In the beginning, it was not easy to relate these drawings to each other based on Gestalt principles, and we only had a few samples in this group. But they seem to represent some particularly creative instances. We decided to name these according to the characteristics they embody - what they do: sparkling, glowing, dripping.

The colour coding of the affinity groups pre-empts a point we will make later when analysing the data tinkerings in the second stage.

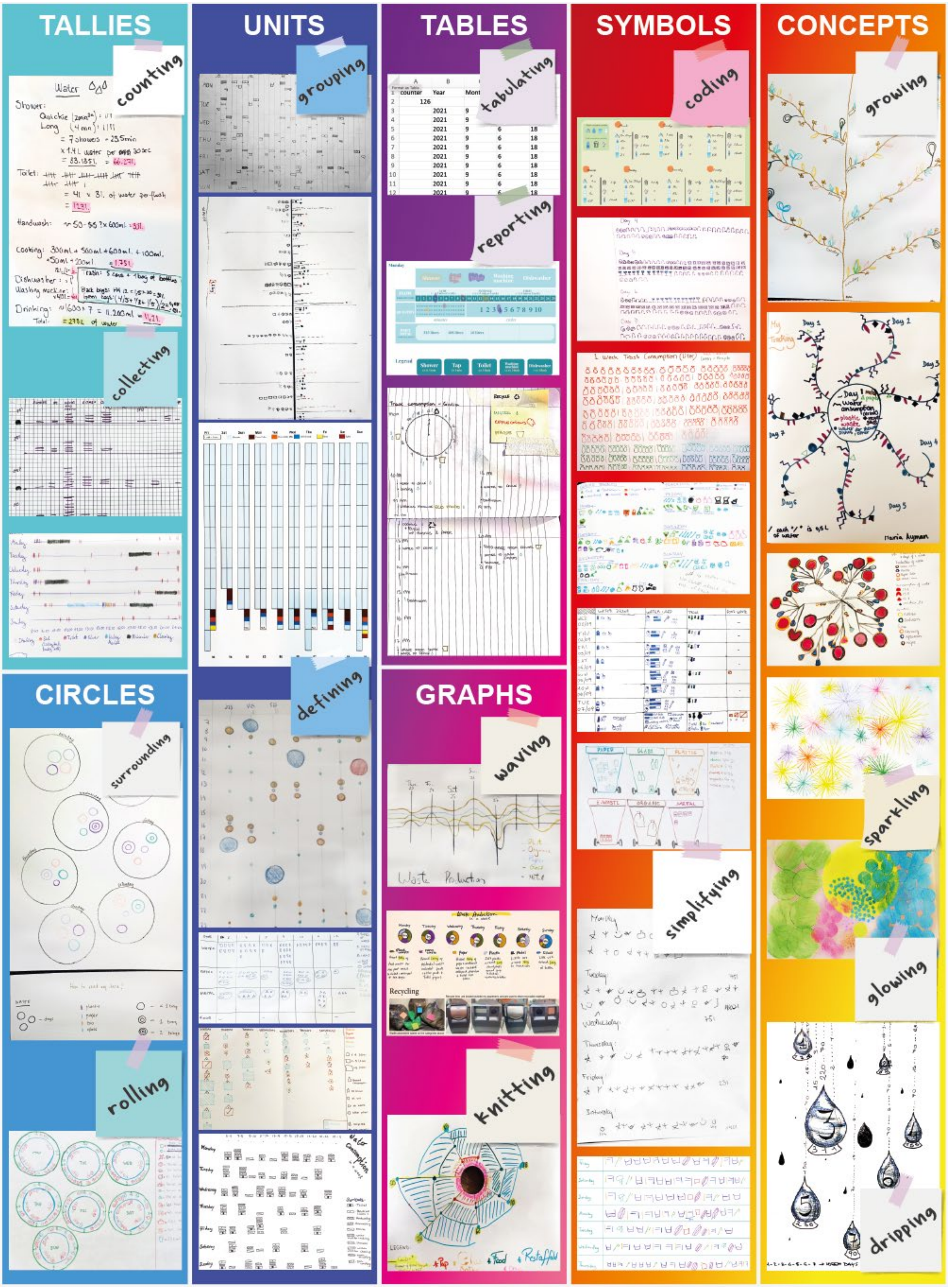


Figure 3. Seven ´Data-Gestalt´ patterns emerge from the analysis of 32 hand drawn data visualizations

Thinkering data-affordances

Scientists have discussed non-human *agency* to understand how people use material objects and, more broadly, the role of materiality in our daily life (Dant 2005). Dant suggests that objects with agencies have the capacity to do something or act like something. He explains the boundaries between daily things and us with practical arrangements through the activities of our bodies.

Gibson (1979) introduces *affordances* to mean the properties or opportunities of the things people perceive in the environment. They provide *`act-able´* features that encourage people to act. In his theory, all affordances are relative and special to their perceivers. Objects afford different actions. To turn Gibson's (1979) theory applicable to human-computer interaction, Norman (2013) defines affordances as *"the possible interaction between people and the environment".* He claims that affordances are not always perceivable; they can be open to interpretation and look ambiguous. As he wants to include designed cues (like icons), Norman (2013) suggests the term *signifiers*. Signifiers can be anything to warn the observer (not) to do something. They can be visible or invisible such as visual signs, sensible objects, or sounds to inform us about the object. When people interact with the object`s signifiers, they start to form conceptual models in their minds. Djajadiningrat et al. (2002) see the affordance theory *"as an invitation to the user for right action"*. They criticise Norman's widening of Gibson's concept of affordances and argue for a direct approach in which action helps to create meaning in interaction: *"(…) A physical object has the richness of the material world: next to its visual appearance it has weight, material, texture, sound etc. Moreover, all these characteristics are naturally linked, (...)."*

To design tangible interaction with the abstract concept of data, there are several kinds of data physicalization methods. Jansen et al. (2015) see data physicalization as a visualisation technique, but beyond that, it enriches data communication and the effects in the presentation of data. With the help of Gibson's Affordance concept, we can better understand how data physicalizations are able not just to communicate data but also to engage people with data.

What participants tinker as 'data-affordance'

We suggest 10 'data-affordance' adjectives (squeez-able, rotate-able, flex-able etc.) and posit that adjectives in act-able form can help us indicate the potential affordances. We also use colour coding for the group making like in the data-gestalt analysis. Our analysis overleaf shows how 'data-affordances' may be formulated as count-able, rotate-able, hang-able etc., Figure 4.

Figure 4. Ten `Data-Affordances´ emerge from the clustering of 30 data tinkering prototypes

Drawing and tinkering consumption habits

Can we trace the effects that data drawing and data tinkering have on how participants view their consumption habits? We analysed the transcripts of what the designers talk about, when presenting and comparing their visualisations. While comparing their data drawings on water consumption, the participants eagerly discuss how they got their numbers:

> *P1: "How did you measure?"*
> *P2: "I looked at the water metre"*
> *P3: "How can we calculate all of the showers?"*
> *P1: "I don't know how much water I use when I wash my hands so I don't think we can calculate…"*

Quite clearly, it is a challenge to measure accurately how much water one is consuming. One young designer is surprised to compare her shower figures with others':

> *P4: "I used 300 ltr per shower. The shower runs 20 minutes, and I never stopped the water before. This week I just kept it that way, so the data is real. And from now on, I mean today is Monday, I will stop the water when I'm shampooing myself. That is less water I guess."*

These are first indications that data drawing raises awareness of how much you consume and may even lead to behaviour shifts. The discussion of waste recycling similarly shows reflections on what sustainable behaviour requires:

> *P5: "It is also important how much space they have in their homes… If you don't have space for individual trash cans…"*
> *P6: "…"*
> *P5: "…I mean plastics and bottles, yes, and paper..."*
> *P6: "There are actually (recycling stations) in my neighbourhood. Most of them."*

Also here, there are indications that data drawing brings forth ideas of more sustainable behaviours:

> *P6: "I went to a 'zero waste wedding' so eventually no waste is useless."*

Even in this short experiment, the designers quite clearly take ownership of their consumption data through the drawing, and there are indications that understanding the data may lead to changes in consumption habits and suggestions for behaviour changes.

When it comes to 'building' consumption expressions through data tinkering, the search for design solutions of how to express the data seems to go hand in hand with a scrutiny of what the data mean. The concept of 'how much' is central in how the participants select materials. When showing a long piece of plastics in his prototype, one designer says:

> *P7: "You can't really understand how much you used water until you measured it…so it basically looks like big"*

> *P8: "And I have the spongy thing for dishwashing and cleaning with water. They will be small pieces. Biggest one for the weekend."*

> *P9: "…green beads they are 5 litres, white ones are 1 litre basically you can count the red ones are 100 litre…"*

One designer finds a creative solution: In her prototype, each weekday is a cup with a number of beans representing data. As the cups are connected, she can flex the construct to collect all the daily consumption into one cup (Figure 5):

> *P10: "…maybe you know how much water you consume in a day but in this way, you can see an overview of the week."*

From listening to the conversations, metaphors play an important role in expressing data:

> *P11: "the pipe was coming from the idea of a drain system."*

> *P12: "Monday is the chair you need to sit, Tuesday is the gamble (dice) if you have to survive to the week, Friday is a beer cup… Saturday is a block because you are blocked…"*

Figure 5. One designer (P10) is flexing her prototype.

> *P13: "Friday has cotton because I am much more productive on that day."*

> *P13: "The shiny ones are for dishwashing because they were cleaned and shine…"*

Some designers take care to express sustainable values in their prototyping:

> *P14: "when you flush you will crush… flowers mean you are very clean in these days…and I put this pig here because you use 35 litre here."*

As for the data drawing, tinkering brings an added focus on the data not just visually but also in the acts that the constructs afford.

'Data-gestalt' and 'data-affordance' as design inspiration

What is the value of the terms we propose? Our goal is to understand better how abstract data may be given intelligible form – visual or physical – to make them easier to understand, engage with and act upon. For designers tasked with turning data intelligible, inspiration from theoretical perspectives is likely to provide support. We have analysed how the data drawings may have inspired data tinkering - how 'data-gestalt' informs 'data-affordance'. We consider the narratives and body language of the participants while showcasing their data tinkerings in video recordings. In many cases, we can see how the same designer brings inspiration from their data drawing across to the data tinkering. In other cases, the designers take inspiration from each other's works. In the following, we have selected the five most clear examples from our analysis.

Do 'Tallies' gestalt inspire 'Count-able' affordance?

One designer, whose data drawing we characterised in the 'Tallies' group, used ear cleaners to represent data in his data tinkering. He uses a similar grouping pattern and repeats the figure-ground relationships with invisible lines of days (Figure 6). We recognised this as a 'count-able' affordance:

> *"I tried to play with the materiality like the cardboards are the days I spent at home. (...) The cotton buds show the overall water consumption for the days."*

Brunswick (1952) expanded Gestalt theory beyond perception. He formulates a functional view of how organisms (not just humans) interact with the environment, how they represent the world, and they affect it. Storkerson (2009) explains Brunswick's term Perceptual Constancy: *"the organism uses multiple cues vicariously to deliver the perception of a constant object in different locations or at different angles."* May we perceive the ear cleaner buds as similar to the drawn tallies as they both offer the affordance of counting? Gibson (1979) also based his Affordance theory on Gestalt theory, as each thing has a way of showing what acts it invites.

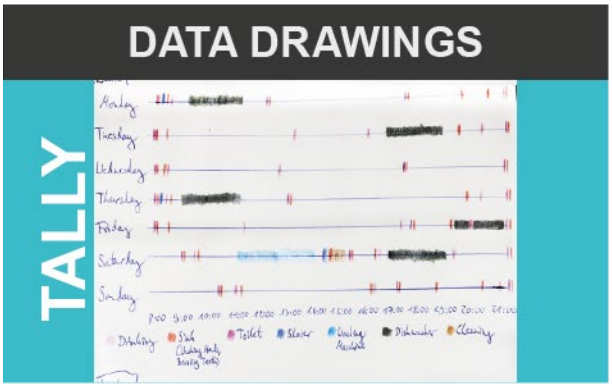


Figure 6. A 'Tallies' data drawing inspires a 'Count-able' data tinkering

'Circles' and 'Rotate-able' constructs:

In the 'Circle' group, one designer transfers her circle concept from the drawing into using different circular objects with some proximities and relativities that represent the data. This means she can now rotate the bottle caps and paper plates to provide different views of the data 'on' them, Figure 7.

> *"The shiny ones are for showers and dishwashing; inside the small caps have the daily amounts with small straws. The house and the colours on the house show the area we use. You can spin like this [turns the plate to show more]."*

Where the graphic circle gestalt communicates a particular view of data, the rotatable tinkered objects allow manipulation, seeing data from several sides.

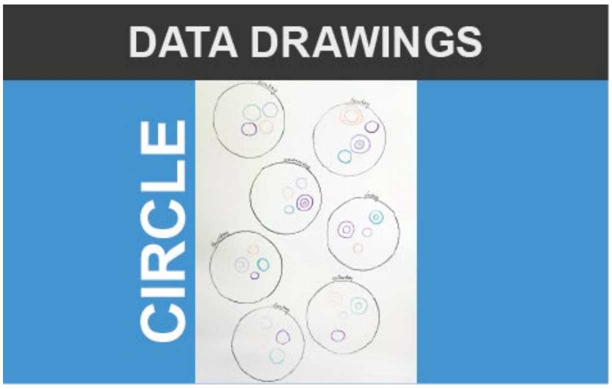


Figure 7. A 'Circle' data drawing inspires a 'Rotate-able' data tinkering

‘Graphs’ gestalt and ‘Trace-able’ affordance:

The waves of the ‘Graph’ data drawing show similarities with the fluctuations in strings in the prototyping in Figure 8. The strings make it possible to trace the data with a finger; it is ‘Trace-able’, and the days are shown in similar ways with sharp lines in both data drawing and data tinkering.

> *“This is flushing* [traces the blue string]*, this is showers* [yellow string], *and you can see how fluctualizing and drinking* [grey string] *is always the same.”*

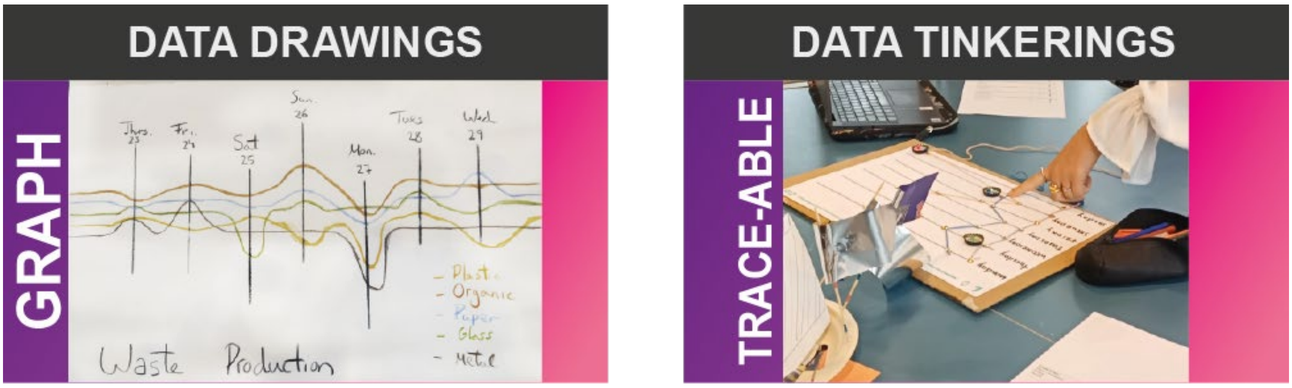


Figure 8. A ‘Graph’ data drawing inspires a trace-able data tinkering

‘Sparkle’ gestalt and ‘Squeez-able’ configurations

Some links between drawings and tangibles are more subtle. The ‘data-gestalt’ patterns that we have termed ‘concepts’ seemed to inspire exotic tangibles. While made by different designers, the colour and material choices by the Law of Similarity support the links between the ‘Sparkle’ data drawing and the ‘Squeezable’ tinkering, Figure 9.

> *“This is flush (He crushes the plastic cup that is turned upside down and surrounded by a ring roughly). The brown-colored ones show final amount of we use for toilet. And the weekend looks more brown because you know...(Laughs)”*

Figure 9. A ‘Sparkling’ data drawing inspired a ‘Squeez-able’ data tinkering

Did ‘Growth’ gestalt inspire a ‘Fly-able’ affordance?

In Figure 10 the designer plays with the same shapes and patterns as in her drawing we called ‘Growth’. In the tree drawing, the branches grow with the amount of waste, in the tinkering, the balloons grow with higher data numbers. Both have the centre of gravity and the same direction of growing from the inside out.

> *“I couldn’t do it, but when I waste more water the balloon would be bigger and bigger by the pipes, and this is going up like this... just imagine it.”*

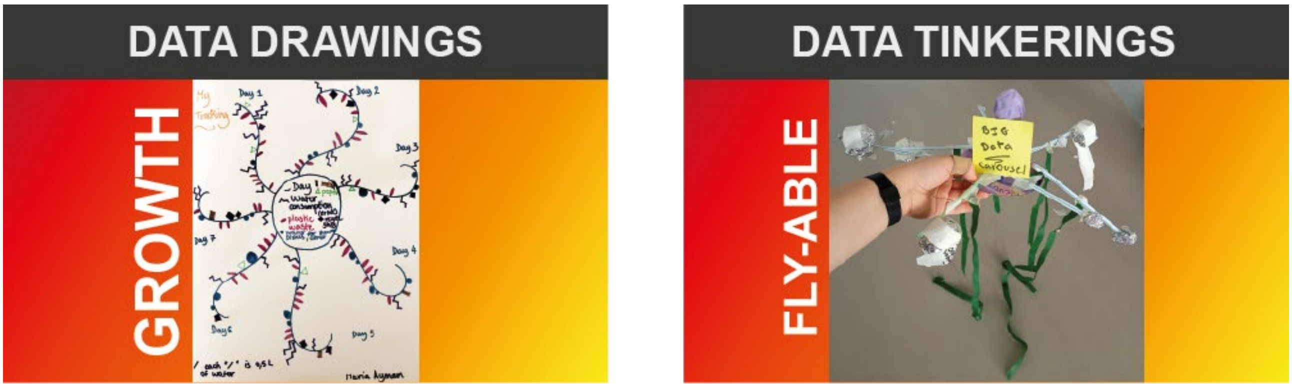


Figure 10. The comparison of growing data drawing and of a fly-able data tinkering

As Brunswick’s theory (1952) explains, gestalt is not a simple perception of elements but an intricate negotiation of many different cues between object and environment. We cannot with absolute certainty point out how data drawings inspired data tinkerings, but there are likely connections. In the five examples above, the data drawings and tinkerings belong to the same participants. But we also noticed how participants working side by side were affected by each other’s designs. They determined their materials by reaching over, passing or sharing materials during physicalization. Even so, we find sufficient resemblances to suggest that our data-gestalt and data-affordance terms may have value not just in recognising attributes but also in inspiring future designs of data prototypes. We have indicated links between data gestalt and data affordances by using to similar colour codes in Figure 3 and Figure 4.

Discussion

Creating data visualizations and data physicalizations is no easy task. What allowed us to develop the concepts of ‘data gestalt’ and ‘data affordance’ was in part the large diversity we got with asking 40 design students to try their hands on the same task and data set. In a subsequent year, with 20 students, we got less variety. In a field as new as this, where standards and exemplars are yet to be developed, variability seems to be the key to developing good solutions. We suggest that our concepts can help widen the design space when introduced upfront.

How did the materials provide influence the data physicalization designs? We asked the participants to bring materials from home to share on a large table, and we also added boxes of tinkering materials from previous projects. On hindsight, we observed several links between materials and prototypes:

Multiple units (e.g. pearls, pipe cleaners, bottle caps, matches) inspire data physicalizations that are count-able and pick-able

Round objects (e.g. paper plates, disposable cups) encourage rotate-able designs

Flexible materials (foam, rubber, plastics, paper) inspire flex-able designs

Strings and threads inspire trace-able designs.

There are most likely other ties, but this would be the topic of another study. In the future, data affordance as a term will help select materials that increase diversity.

On the question of how data drawing and data tinkering inspire participants to consider their own habits and potentially give rise to behaviour change, our evidence is circumstantial. From the discussions transcribed, there are indications that the participants become aware of the challenges of measuring, comparing, and changing water consumption and waste habits. We believe that the attention to personal behaviours is caused by the drawing and tinkering activities, but we cannot with certainty say that an enthusiastic discussion of sustainable behaviours wouldn't bring about a similar focus. We do, however, observe that the students, develop ownership to their designs and hence perhaps make a coupling between data, designs and behaviours.

Conclusion

We suggest that the methods of data drawing and data tinkering are powerful means of engaging young people with self-tracking data and that they help increase awareness of sustainable behaviours.

Data drawing proves an incentive for the participants to reflect on their own behaviours. They trigger the participants to share experiences of consumption and recycling with their peers by comparing and clustering of their drawings. In our attempt to understand what inspires the participants' drawing styles, we observe that data drawings can be clustered into different Gestalt patterns. We suggest the term 'data-gestalt' to name such patterns according to their shapes and semantics.

Data tinkering challenges the participants to express data in unconventional ways. They look for methods of conveying numbers, sizes, and volumes, and they explore metaphors to add meaning. Being designers, they willingly explore different materials, textures, and aesthetics – this may be less dominant with non-designers. Most excitingly, our analysis of the data tinkerings shows a range of affordances that we venture to call 'data-affordances' and express in a Gibsonian style of 'act-able' adjectives. Tangible expressions of affordances seem to have great potential for engaging people in exploring data.

Very promising are the observations that many of the participants, through data drawing and prototyping, become aware of their consumption habits and of possibilities for behaviour changes. We observe that the raised awareness of the participants is a consequence of prototyping the data and not simply of being stimulated by the social experience of an enthusiastic design student group focusing on a topic as a whole.

There are similarities between how participants draw data and how they make a prototype of data. Some participants show similar colours, shapes, or symbols between their visual and physical expressions. The fact that we are able to trace lines of inspiration between certain kinds of data drawings and certain kinds of data tinkerings make us optimistic in suggesting that our terms data-gestalt and data-affordance may serve as inspiration for designers to engage more visually and physically with data, thus making abstract data easier to grasp, engage with and act upon.

References

Anderson, K., Fafus, D., Rattenbury, T., & Aipperspach, R. (2009). Numbers Have Qualities Too: Experiences with Ethno-Mining. Proceedings of Ethnographic Praxis in Industry Conference.

Brunswik, E. (1952). The conceptual framework of psychology. Chicago: University of Chicago Press.

Buur, J., Mosleh, S.S., & Nielsen, C.F. (2018). Data Physicalization in Ethnographic Contexts. Ethnographic Practice in Industry Conference

Buur, J., Sorensen, J., & Cooper, C. (2021). Big Data and Small Beginnings – How People Engage with Data Physicalizations. Proceedings of Nordic Design Research Conference, Kolding, Denmark.

Dant, T. (2005). Agency, Affordance and Actor-networks. In Materiality and Society. New York, NY: Open University Press, 60–84.

Djajadiningrat, J.P., Overbeeke, K.C., & Wensveen, S.A. (2002). But how, Donald, tell us how?: on the creation of meaning in interaction design through feedforward and inherent feedback. DIS '02.

Dragicevic, P., Jansen, Y., & Vande Moere, A. (2019). Data Physicalization. Springer Handbook of Human-Computer Interaction, Springer.

Ellis, W. (1999). A sourcebook of Gestalt psychology. London: Routledge.

Evergreen, S. & Metzner, C. (2013). Design principles for data visualization in evaluation. In T. Azzam & S. Evergreen (Eds.), Data visualization, part 2. New Directions for Evaluation, 140, 5–20.

Friday for Future Movement (2018) Retrieved January 27, 2023, from https://fridaysforfuture.org/

Gibson, J. J. (1979). The ecological approach to visual perception. Boston: Houghton Mifflin.

Global Sustainable Development Report. GSDR. (2019). The future is now science for achieving sustainable development. Retrieved January 27, 2023, from https://sdgs.un.org/publications/future-now-science-achieving-sustainable-development-gsdr-2019-24576.

Jansen, Y., Dragicevic, P., Isenberg, P., Alexander, J., Karnik, A. et al. (2015). Opportunities and Challenges for Data Physicalization. Proceedings of the ACM Conference on Human Factors in Computing Systems.

Karyda, M., Ryöppy, M., Buur, J. & Lucero, A. (2020). Imagining Data-Objects for Reflective Self-Tracking. CHI '20: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. New York: Association for Computing Machinery, 12 p. 715.

Kawakita, J. (1982) The Original KJ Method. Tokyo: Kawakita Research Institute.

Koffka, K. (1963). Principles of gestalt psychology. Harcourt, Brace & World.

Kools, S., McCarthy, M., Durham, R., & Robrecht, L. (1996). Dimensional analysis: Broadening the conception of grounded theory. Qualitative Health Research, 6 (3), 312-330.

Laschke M., Hassenzahl M., Diefenbach S., & Tippkämper M. (2011). With a little help from a friend: a shower calendar to save water. In CHI '11 Extended Abstracts on Human Factors in Computing Systems (CHI EA '11). Association for Computing Machinery, New York, NY, USA, 633–646.

Lupi, G. & Posavec, S. (2016). Dear Data. Princeton Architectural Press.

Norman, D. A. (2013). The design of everyday things. MIT Press.

Pandey A. V., Manivannan A., Nov O., Satterthwaite M., & Bertini E. (2014). The Persuasive Power of Data Visualization. IEEE Transactions on Visualization and Computer Graphics, vol. 20, no. 12, pp. 2211-2220, doi: 10.1109/TVCG.2014.2346419.

Storkerson, P. (2009). Experiential Knowledge, Knowing and Thinking. Proceedings of Experiential Knowledge Special Interest Group 2009 (EKSIG09), London, UK.

Sustainability Development Goals. SDG. (2022). Bringing Data to Life. Retrieved January 27, 2023 from https://unstats.un.org/sdgs/report/2022/flip-book

Ware, C. (2012). Information visualization: Perception for design (3rd ed.). Waltham, MA: Morgan Kaufmann.

Ayşe Özge Ağça

She is industrial designer and PhD fellow with research into the potential role of data physicalization in designing solutions towards (un)sustainable consumption behaviors.

Jacob Buur

He is professor of User Centred Design with prior UCD management experience in manufacturing industry. He advances the concept of 'participatory innovation' and researches how video and physical objects empower collaboration between stakeholders in innovation projects.

Prototyping as making sense of expressions

Martin A. Padalak, IxD Lab, IT University of Copenhagen
Tom Jenkins, Department of Digital Design, IT University of Copenhagen

Abstract

Prototyping is a complex process of navigating a chaotic design space. Especially when there are few criteria for success, it is often difficult for a designer to know what direction to follow. We argue that prototyping can be considered as a process of sensemaking driven by finding the right expression of a design goal. To illustrate this, we present the case study of the aural-visualiser 1000, a functional refined prototype that resulted from an open-ended design project. Using its process as an example, we abstract important expressions that informed the design and prototyping of the aural-visualiser 1000, pointing to when the conception of the project changed and how that affected our making sense of the design space. We reflect on this design process to articulate productive pivots and tensions that led to the finished artefact.

Prototyping; expression; sensemaking; presence; listening

Introduction

We navigate design spaces by prototyping: prototyping gives us insight into what works and what doesn't work for the decisions that we make during a design process. These decisions constitute the design process, and understanding how and why these decisions work the way they do is one way to better understand how design works. This comes relatively easily when a problem is straightforward. In a well-specified design space, where a context is well-understood, and a design problem has a set of given constraints in play, it is relatively straightforward to see what makes a design successful—what works well to satisfy those constraints for that context is clear.

In practice, though, the process of design is usually murkier. Design is a process of inquiry that often has no set criteria for success, and as such no well-defined heuristics or decision-making structure to give designers an obvious route to follow. These qualities have been highlighted as ways that design can engage productively with so-called *wicked problems*, problems so broad that they defy simplification, and involve any number of factors that together prevent them from becoming tractable and well-articulated (Rittel and Webber 1974; Buchanan 1992). In these situations, design spaces and directions are not so clear, and the relation between the problem and prototype can sometimes become occluded. On a less grandiose scale, many popular genres of contemporary constructive design research such as critical (Dunne 2006; Dunne and Raby 2001), speculative (Auger 2013; Dunne and Raby 2014), and discursive design (Tharp and Tharp 2019) often lack overt design problems as such. In practice, designers operate comfortably in spaces like these. Indeed, the process of designing a kettle or app looks quite a lot like designing critical or speculative design projects

(Boer and Jenkins 2021). Materially, the processes of prototyping and interpreting prototypes are similar no matter the topic—they're joined by design.

One reason for this similarity is in the thinking about the problem. Kolko has described design ideation and decision-making as a form of *sensemaking*, where a designer uses a combination of their personal experience and design materials to make sense of a design space by producing ideas and prototypes that help articulate it (Kolko 2010b). We argue that this direction is based on a designer's sense of what a design artefact *should be* to satisfy the goals of the project. While this may seem obvious—after all, Nelson and Stolterman have described design as moving away from that-which-is and producing that-which-ought-to-be (2012)—we believe that there is value in taking this idea seriously and using a design case to reflect on how it works in practice, developing ways to articulate the knowledge of a design space that prototyping produces. Building on Hallnäs and Redström's idea of the *expressional* (Hallnäs and Redström 2002a; 2002b) and Nelson and Stolterman's idea of *desiderata* (Nelson and Stolterman 2012) we describe how an open-ended prototyping process is driven by what best expresses (or fails to express) a designer's intention for a given context and situation.

This paper presents motivations, decisions, and reflections made during designing a particular artefact as an example of the kind of sensemaking described above. We walk through the design process of the aural-visualiser 1000, a portable listening system that listens to audio in the world and transforms it for later reflection. First, we describe our theoretical background. Then we walk through our case in stages: developing a design space, describing goals of the design process, and discussing how those goals were manifested through prototyping. Finally, we close with reflections on how expression and working with tensions helped us make sense of our design practice.

Figure 1: The completed aural-visualiser 1000

Background

How designers navigate a design space has been described as a kind of *sensemaking* where the design problem and its definition changes over time as designers engage with it (Eklund, Aguiar, and Amacker 2022; Kolko 2010a; 2010b). This sensemaking builds upon a combination of designers' experiences, goals, research, and any number of other factors. As a practice, though, "sensemaking" is active and subjective, "a process that is personal and contingent on experience, that substantiates learning, that takes place continually and forever, and is fundamentally based on each participant's perspective or point of view" (Kolko 2010b). Here Kolko describes sensemaking as a kind of perpetual reframing that helps a designer gain knowledge about a design problem to understand it more concretely. Russel et al have described sensemaking as "the process of searching for representation and encoding data in that representation to answer task-specific questions" (Russell et al. 1993), and later as "the process of creating a representation of a collection of information that allows the analyst to perceive structure, form and content within a given collection" (Russell et al. 2009). To Kolko, this is a form of modelling a problem, a way to interpret information that can become input to a design process where design ideation can occur and be evaluated (Kolko 2010b). In prototyping, these design syntheses are constructed so the designer can establish whether a manifestation "works" to support the design idea.

Expressions in interaction design

When Hallnäs and Redström wrote that "functions reside in the expressions of things" they meant to turn the Bauhaus idea of "form following function" on its head. Rather than the form of an object being derived from its functionality, they assert that in interaction design, one can propose new functionality by searching for expressions of them (Hallnäs and Redström 2002b). Expressions offer a perspective on what a design is saying, what is being projected, and possibly what a design could mean in a particular context or setting. Landin describes expressions of interaction as "expressions of how people might relate to the interaction with the design, in certain contexts" (Landin 2009). As a way to understand *possible* use, expressions are reminiscent of affordances (Gibson 1977; Norman 2013). However, these are not the use-qualities of already-existing objects, as affordances are. Rather, they refer to how the qualities of a design can be expressed. What to express, naturally, is highly situated and contingent in design. As an "ultimate particular," a prototype is based on a context and setting that is not generalizable (Nelson and Stolterman 2012). While this may pose a problem to producing broad design theory, the selection of these expressions and the decisions that are made to achieve them as aesthetic goals in a particular case can act as examples of how design works more broadly.

Expressions as a target of sensemaking via desire

It is in this mode that Lim et al's idea of *filtering* and *manifestation* (Lim, Stolterman, and Tenenberg 2008) can help to make sense of sensemaking as the key activity of design. Prototypes serve to manifest aspects of a design space for evaluation, operating as a filter for the designer to evaluate their success, reflecting on their activities there (ibid). But how does a designer identify what works? The criteria for evaluating a prototype—what a designer learns through this process of sensemaking with a prototype—links back to Nelson and Stolterman's idea of *desiderata*: the designer reflects on whether the prototype is successful in conveying their vision, here through its expression. Especially with open-ended briefs, the prototype is a way to project intention into the world, to probe the possibilities of a design space and see what emerges and whether it fits a particular vision. Kannabiran and Bødker have called prototypes *objects of desire*, "invoking familiarity with past practices while simultaneously piquing our curiosity about possibilities for shared technology mediates futures" (Kannabiran and Bødker 2020).

To illustrate how these bits fit together as part of a design prototyping process, we describe a project that took a very open-ended brief and made a prototype reflecting significant design intention. We use it to illustrate how the sensemaking described above occurs in practice.

Case Study: Constructing the aural-visualiser 1000

Our case study comes from a four-month design sprint based on a class project in interaction design at the IT University of Copenhagen. Groups of four masters' level interaction design students together responded to the broad topic of "Energy Futures". The goal of the course was for students to develop a design brief that resonated with them, create prototypes to that brief, and refine the prototypes into something reflecting their stances as designers. Given just 14-weeks, time was short, and quickly developing constraints was necessary to define a context that worked for the project. This case study is ordered approximately chronologically. However, as with most design processes, this project did not develop in a linear way. It followed any number of paths to dead ends and had to navigate less-than-clear goals and ambiguities to develop a meaningful prototype.

Engaging with the design space and developing a brief

The project began by engaging with energy broadly, narrowing into the topic to find a compelling design space that we could refine to an interesting design brief. Inspired by Pierce and Paulos (Pierce and Paulos 2012; 2010), we focused on the idea that energy could be harvested and materialized. Initially, we worked in a dystopian future, or science fiction context, imagining humans needing to produce energy through their everyday life with their bodies, or harvested from materials like hair, spit, and sound. The future gave us flexibility to imagine something that might not be so plausible in the present and opened new possibilities for designing novel interactions (Auger 2013; Candy 2010).

Figure 2: Science fiction influences. Nausicaa: Valley of the Wind (1984); Raised by Wolves (2020); a generic VR headset (that we understood to draw energy from its wearer); Pierce and Paulos' Energy Mementos (2010); Akira (1988); The Matrix (1999).

The moodboard above (Figure 2) made it clear that our interests lay in exploring how energy could be absorbed, mediated and expressed, and not in solving a specific problem or designing a conventional product, at least at the time. We chose not to have a specific user or target group in mind, developing instead in a more abstract, interaction-driven way (Maeng, Lim, and Lee 2012). After a short while, we decided to work with sound as a form of "energy," finding it more relatable and tangible. We became inspired by sound waves and their various representations (Figure 3). Choosing sound led us to a range of material inspiration to draw from, from microphones and gramophones to speakers and public address systems.

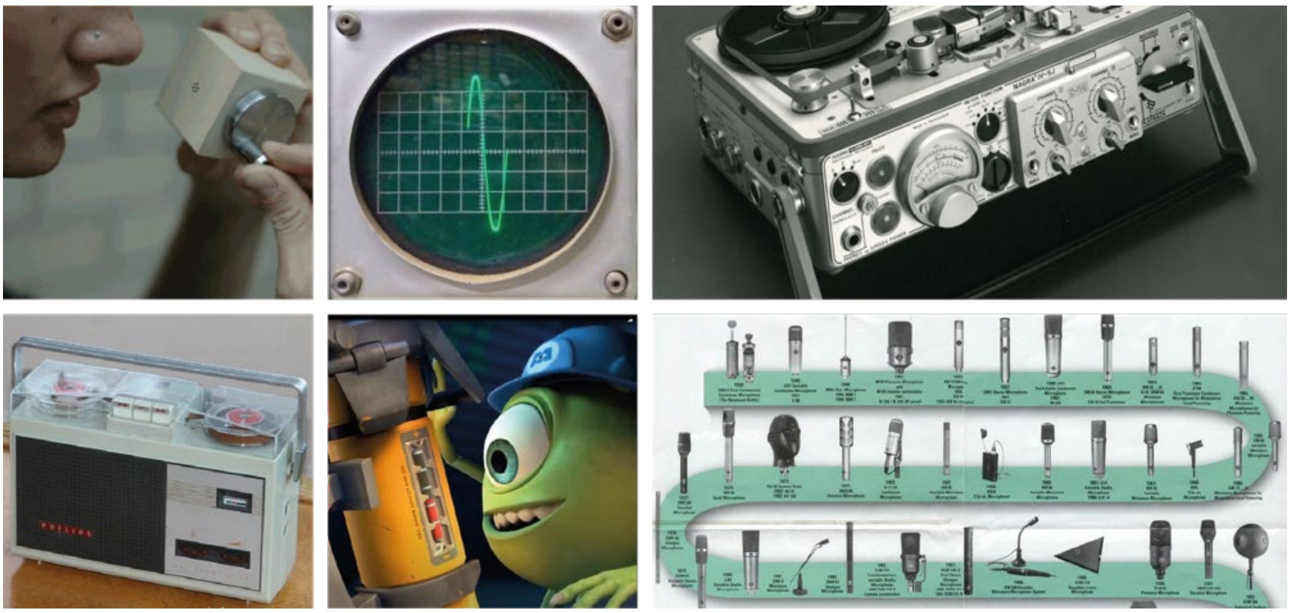


Figure 3: A moodboard of how sound might be gathered and represented. From left, Pierce and Paulos' Energy memento (2010); an oscilloscope screen; a retro field recorder; a 1960s tape player; the scream tanks from Monster's Inc. (2002), the evolution of microphone hardware.

Thinking with sound led us to imagine a system that captures and represents the presence of sound as an elusive and momentary thing, while at the same time making it more durable. This led to a design brief:

When perceiving sounds most of us rely solely on our hearing. To broaden this experience, we seek to materialise sounds with visual representations. As with all forms of energy, sound has an elusive nature. To work with and explore this elusiveness, the artefact should produce mementos of the representations, allowing a user to save, compare and contemplate on them.

This design brief became a storyboard (Figure 4):

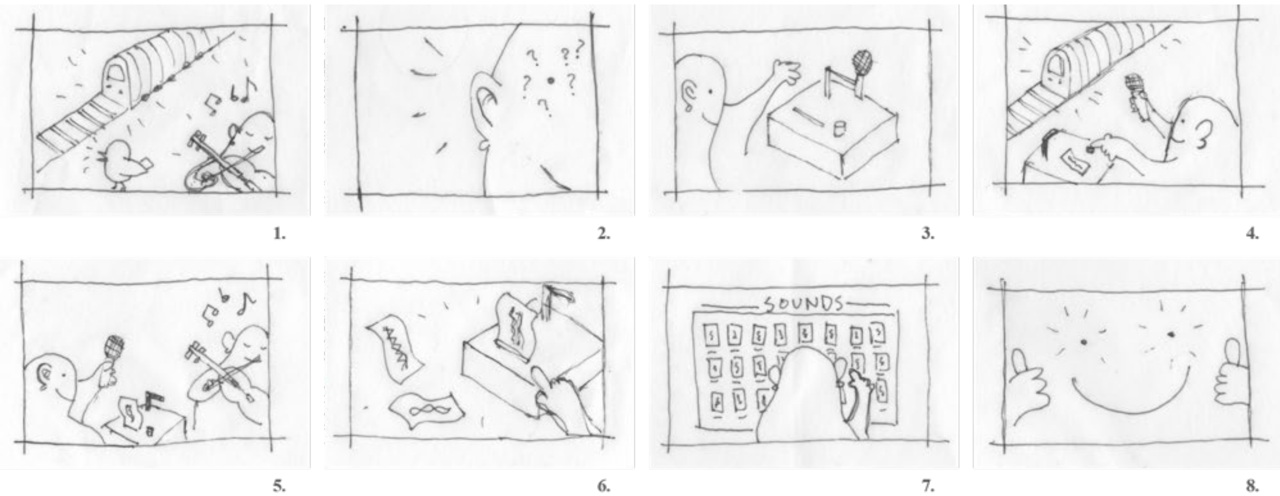


Figure 4: Storyboard of design brief. (1) In the world, sounds are happening: a train, a bird and a violinist. (2) A figure hears them, but unable to see the sounds themselves, they question how they might look. (3) The figure orients themselves towards a device holding a stereotypical microphone, and (4, 5) brings the device to the sounds to capture them. (6) The device produces small prints of the sound. (7) Elsewhere, the figure studies the prints, now hanging in a grid each above a notation. (8) Their eyes are gleaming, having looked at sounds and their differences

Expressing listening through interaction and form

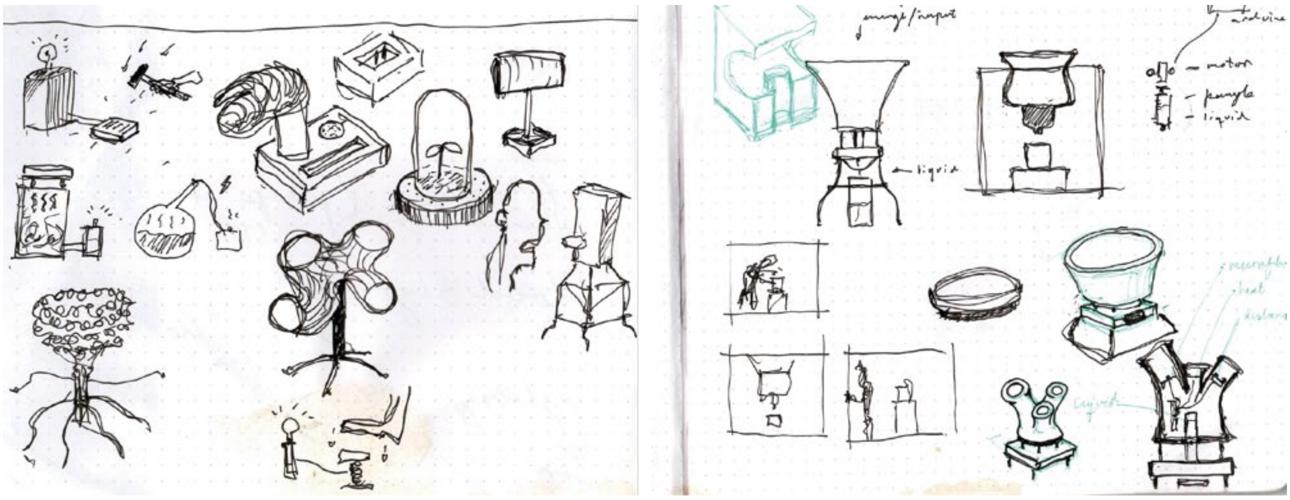


Figure 5: Early form sketches for energy capturing devices, including sound.

What should a thing that captures sound look like? Our early concepts were inspired by all sorts of materials, inputs, and systems, from distillation metaphors, to microphones, to organic forms and plant life (Figure 5). For sound, we began with the idea of a gramophone to capture local audio, producing a cardboard model that represented this first concept.

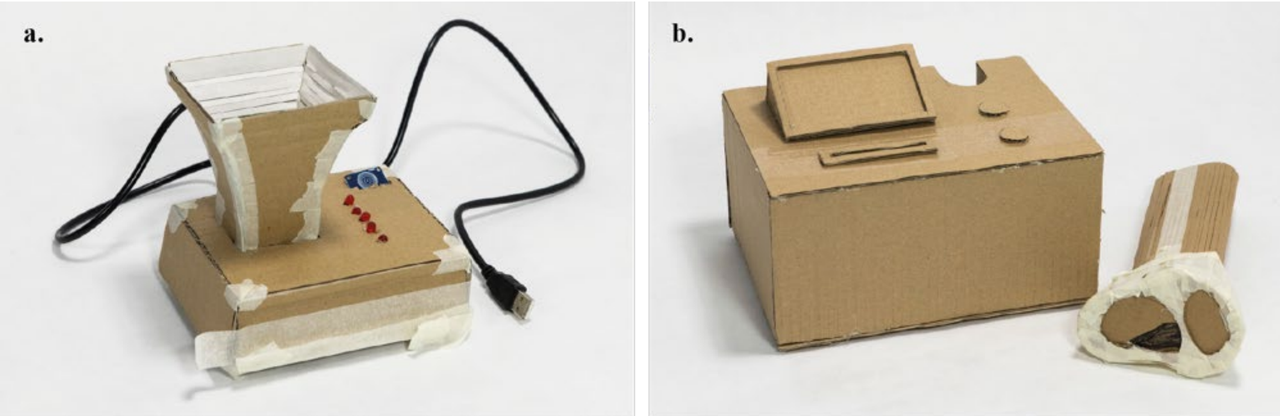


Figure 6: The first prototypes delved mainly into manifesting physical using waste cardboard, glue and tape.

The first prototype (Figure 6, a) explored cultural references to sound and a basic interaction that required a user to make loud noises into the funnel. These would light the LED's one by one, after which the button would activate a piezo buzzer, "returning the sound". We found the gramophone to be too mundane, and the interaction as one requiring too much effort. We were also limited in this concept to record only sounds that took place nearby. Still, the prototype confirmed a potential to us in working with sound to develop novel interactions.

The second prototype (Figure 6, b) demonstrates the use of form as a focal point for exploring functionality. A dummy-display let us weigh the pros and cons of including a screen in the design object and resulted in our decision to focus on printing alone as the sole output. To reduce size we opted for printing alone. A key moment was realizing that the funnel of the first prototype could be detached from the body, changing the metaphor for this sound harvester from simply hearing what was nearby to more intentional listening. *Listening* became a way to frame the interaction, becoming a key measure of the expression we sought. The early flashlight form allowed for more targeted, direct engagement with the world. Though originally a whim, the ear expressed listening in a fundamental, playful way.

These first prototypes were essential to better understand our design space—by manifesting ideas in the real world, we could determine what did not work, informing and defining our vision. We learned that it wasn't about visualizing sound in particularly compelling or complicated ways, it was about framing attention to the surrounding environment.

Figure 7: Designing for sensory presence beyond the visual.

Defining the form took place in parallel with obtaining new inspiration from outside the project. Focusing on one human sense began to resonate in new ways as we drew on the work of Finnish architect Juhanii Pallasmaa. His book *The Eyes of the Skin* (Pallasmaa 2012) describes how contemporary design practices such as architecture enforce a "hegemony of the eye" meaning that the world is to be seen rather than lived in. Designing to accommodate other senses like hearing, touch and so on creates a more complete way of being in the world, offering richer experiences and a more meaningful sense of presence in it. Notably here, this idea of "presence" reverses some of the original design framing: rather than thinking of "presence" as the presence of energy, it reflects a person being present in the world. Pallasmaa goes on to note that "vision separates us from the world whereas the other senses unite us with it" (28, ibid). This helped us to reframe the problem as *listening* to become more present in the world and confirmed our decision to abandon real-time representation of sounds on screens. A new design space emerged (Figure 7).

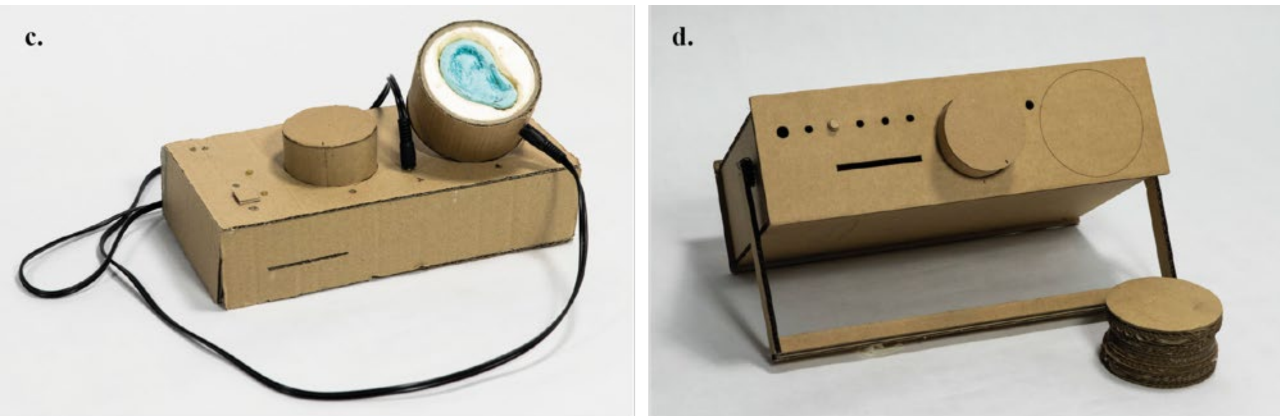


Figure 8: Refining form in cardboard.

Taking listening seriously led to some changes in the design concept. A more compact form (Figure 8, c) supported the idea of portability—so one could bring the device with you to listen in new places—but was too small to house the necessary hardware. We introduced a dial allowing for a way to set the length of a recording. Nesting the ear in a casing, removing it from initial view, was to build tension between first impressions and later interaction, making choosing to listen feel more intentional. The ear became more like a human's. While this was still a cardboard prototype, a mini-jack cable was added to increase the prototype's resolution and enhance our team's discussions.

The final form prototype (Figure 8, d) underscored the design variables we had uncovered through the prior manifestations. This higher fidelity enabled us to determine the interface layout: dimensions for faceplate holes and buttons, evaluate proportions and plan for buying materials. We added the handle to express portability, sensible for a device meant explore sounds in different environments. Compared to prototype before it (Figure 8, c), its bigger casing had plenty of space for the hardware being developed concurrently, so we reduced the size again. To indicate the earcup can be detached from the case we designed a housing that could also be a place to wrap the mini-jack cable. This form took its cues from scientific instruments, as they mean to reveal the truth of the world. At the same time, the earcup is intentionally playful, making the interaction slightly ironic and drawing attention to the interaction itself—ideally supporting a user to become more present through its use.

Developing a Materialization of Experience

As described in the brief, the project was about capturing energy's elusiveness. In the storyboard (Figure 4), it became clear early on that the energy in question was sound: gathered by the device, it was materialized for reflection. One of the earliest things that was clear about this project was that the sound gathered by the device should be made physical, producing a material token that stored what the device heard. This reflects certain formal qualities from the body of the device, documenting what it records as a kind of scientific instrument. Inspired by the lines in an oscilloscope's display (Figure 3), we tested creating our own sound representations. Experiments here included using a laser, mirror, and a speaker to generate shapes reflected across a moving membrane (Figure 9, right), and printing coordinates for a sound-atlas instead of the sound representations (Figure 9, left).

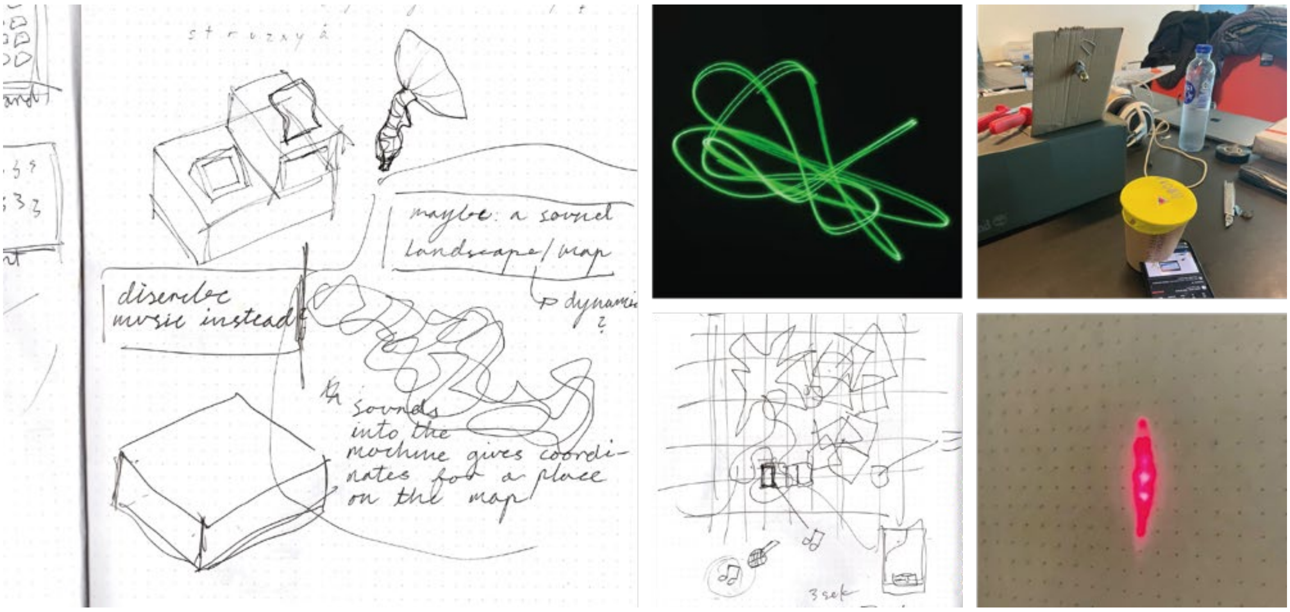


Figure 9: Early sketches and tests for sound representation.

These tests produced shapes we liked, but we couldn’t make this visualization portable. To do that, we moved to software. Prototypes generated with the Processing sound library (Figure 10, a) confirmed to us a potential in visualizing sounds using waveforms as a metaphor. We continued with representing sound attributes radially (Figure 10, b), mimicking the laser experiment. However, the clutter produced from longer recordings and including additional parameters became difficult to decipher. Embodying too much complexity became counterproductive to encouraging exploration of one’s surroundings.

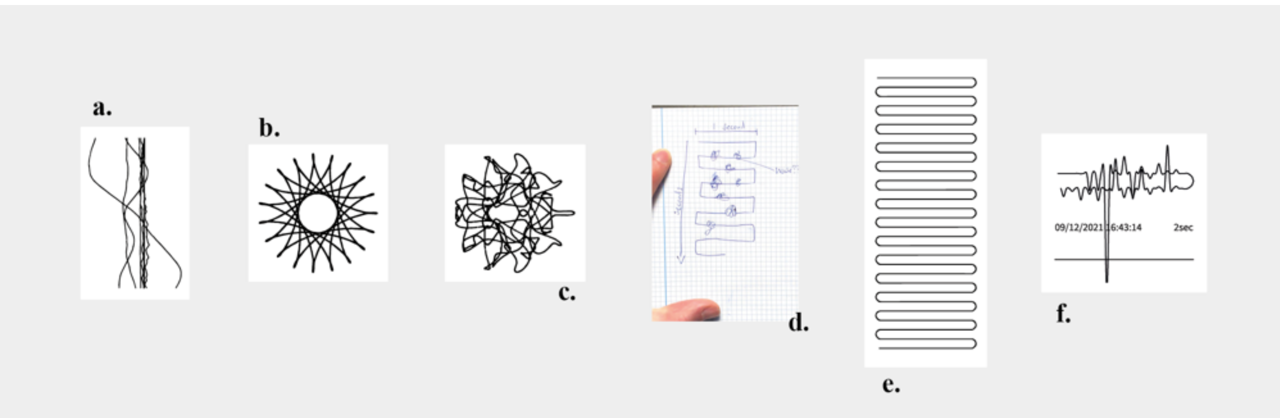


Figure 10: Refining the sound memento

As we refined the visualizations, we found ourselves returning to simpler waveform representations. This shift also allowed time itself to develop the form. A meander structure (Figure 10, d) was able to convey the temporal aspect of sound well. It could be more easily understood while also making better use of the thermal printer, creating denser representations of time. Adding the date and duration of the recordings as well as a line for making a note helped to codify the memento object as something that represents a specific moment (Figure 10, f).

The form that these objects took changed as part of our prototyping process. In general, the visualization was meant to correspond to a sound while leaving some room for interpreting it, instead of capturing audio and presenting it directly. As in the earlier section, the concept evolved to help us think about what the object meant and what it does as part of the broader system. Rather than be strictly documentarian, it became augmented in the process. The simple receipt began to embody dynamics of synaesthesia, the coupling of senses, to reproduce a "fuller" experience of being in the world.

Consequently, the significance of memento also shifted: instead of storing the sounds as energy it now stores meaning, the experience of the presence of sound. As with the form of the device changing from *hearing* sound to *listening* to it, the memento—now firmly described as such—shifted from an expression of *capturing* to an expression of *remembering* something meaningful. This is evidenced in how we imagined these mementos to be kept and stored (Figure 11).

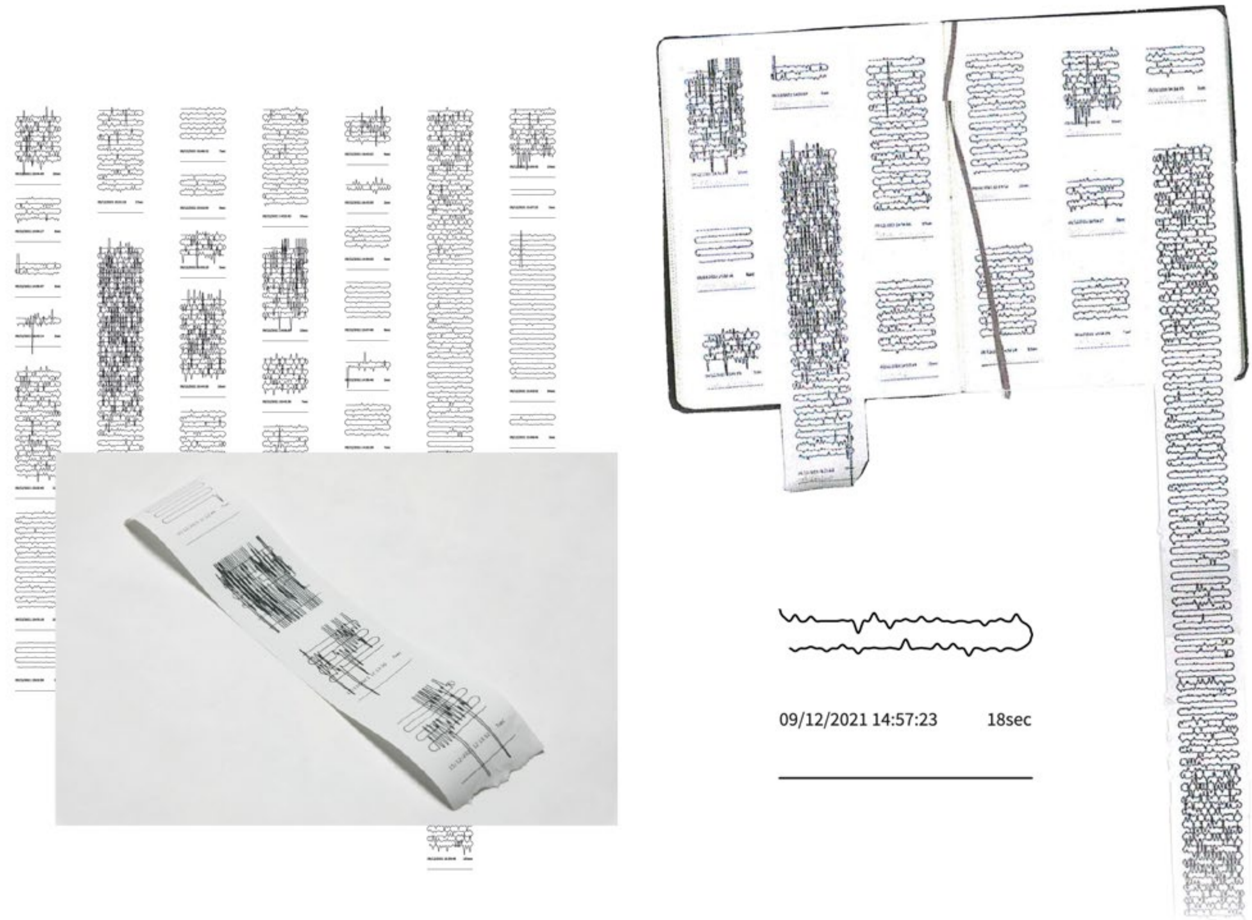


Figure 11: Memento details and how they might be collected in a journal.

We hoped that collecting sounds could inspire a user to explore the multitude of sounds surrounding us, charting their differences and similarities. The printer prints a seamless record of events. They can be torn by the user as desired to collect different recordings in a single event, or to separate discrete moments. Longer recordings (Figure 11, right) might result in comically long mementos to underscore the aural-visualiser's kinship to scientific equipment such as seismographs, while also rendering the temporal element of the mementos easier to understand. Underneath each waveform on every memento is a timestamp of the recording and its duration, as well as a place for a handwritten note: a feeling, a place, what was being listened to, and so on.

Refining the expression

Once the main expressions of the project were decided, we needed to further refine the prototype, developing more polished interactions as well as a more physically finished form. Ultimately, this refinement process created a more compelling final prototype, one that was more convincing and expressive of our design intention.

Figure 12: The Dieter Rams-Designed Braun T 580 Transistor Radio (https://www.moma.org/collection/works/4084)

Many of the visual references we were working from had a kind of nostalgic bent to them, imagining nicely designed objects from the past and how the form language and design qualities that they offer could be adapted to give our system a particular quality. Inspired by the mid-century designs of Dieter Rams (Figure), among others, we sought to create a simple, elegant interaction that made a relatively strange concept approachable and understandable. This echoes the broader design goal of making the complexity of the world more legible and approachable.

Figure 13: Details from final refinement and the interface.

To ensure a high level of finish in the final prototype, we tested tolerances of combining 3D-printed and laser-cut materials to ensure that parts fit together well (Figure 13). Simplifying overall construction, we designed custom brackets and built a section-model to confirm their sturdiness. To reduce costs, we used alternative materials such as cutting and melting cord for the rubber brackets on the aural-visualiser's base or wrapping the handle in electrical tape. Final form decisions were made to both bring together different parts of the system as well as refine the overall expression of the prototype. The handle was designed to double as a stand when in use. A cable hook was added on the side for the power cord and rubber corners at bottom. These emphasized ruggedness and portability to suggest that the system should be brought out into the world to find interesting things to listen to. Finally, the front plate was designed and refined to evoke the kind of mid-century interactions we aspired to, undergoing many iterations to get the look and feel correct.

The aural visualiser 1000

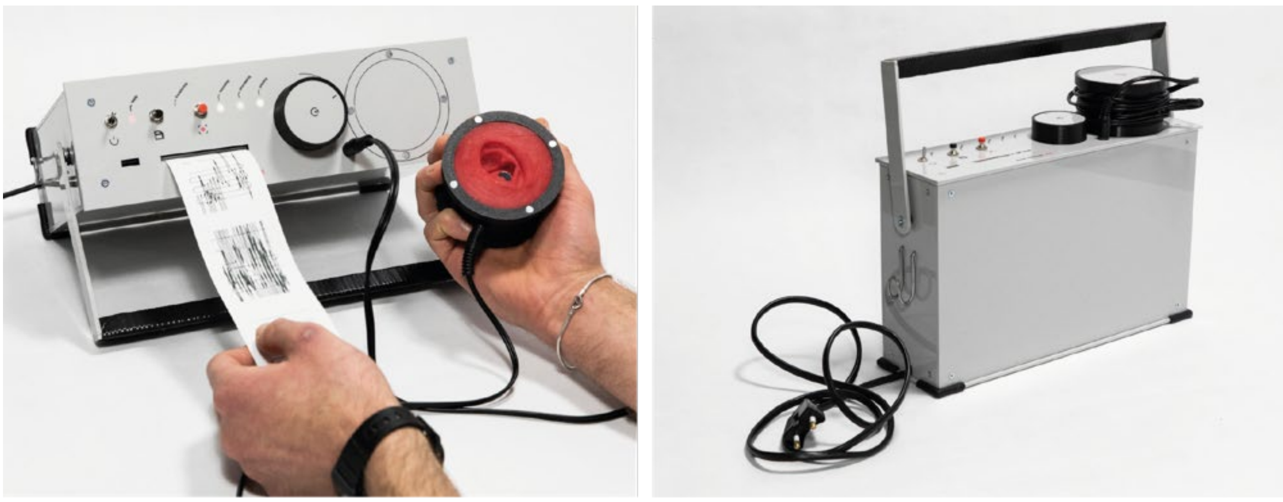


Figure 14: The final aural visualiser 1000. Left, printing visualization, and right, ready to be moved.

The aural-visualiser 1000 is a refined design prototype whose expression asks users to pay attention to the world in a new way. By emphasising the aural and auditory component of an experience rather than the visual component, it seeks to reframe that experience and increase a users' sense of being present in the world. As an antidote to a recorded image sometimes seeing "truer" than direct experience (Padalak and Jenkins 2022), the aural-visualiser 1000 extracts and analyses the energy and attributes inherent to sound, producing a manifestation of that sound for the user to save, compare and consider later. These representations correspond to the recording, but do not recreate it, demanding experience to understand them. The artefact encourages exploring sounds in everyday life, giving perspective on their immateriality and elusiveness. These mementos store a representation of meaningful events or hidden aspects of everyday life for reflection and reminiscence.

Figure 15: Listening to the world, the aural-visualiser 1000 in use, detecting interesting experiences

Discussion

The aural visualiser case study illustrates a process of engaging with an uncertain design space. It provides two ways to understand how prototyping made sense of this space using expression as a lens.

Pivoting as expression-finding

One of the main things that this case study reveals is how *pivoting* to new expressions gave us both traction in and new material for the design process. Capturing energy as sound became *hearing;* making this hearing more intentional and focused led to the idea of *listening;* listening filtered through Pallasmaa became *presence*. Each shift motivated significant design decisions. After Lim et al, the cardboard prototypes used as "design thinking enablers" that helped us to "organically and evolutionarily learn, discover, generate, and refine designs" based on the expressions that we found during the process (Lim, Stolterman, and Tenenberg 2008). Transforming hearing to listening led us to understand the design space in a new way and gave us new directions to orient ourselves towards. Likewise, a simple idea of a physical token to store and *capture* that energy became recast as mementos that support *remembering,* driving a shift in materials from lasers, to software, to ultimately paper. This shift in how we saw the expressions leads to how we reframe knowledge from the prototype.

Taking the materials seriously in this process led to iterative refinements that tuned this expression as the design brief became more nuanced over time. By paying attention to the interactive qualities of these materials and judging how they contributed to the expression of the design goals, in this case how listening and remembering can build new ways to understand presence, the prototype responded to the shifting brief. Hallnäs and Redström note the significance of the expression and aesthetics of computational things (2002b). For us, having a strong design concept made the process of finding the next step of the process more tractable—certainly not simple, but operating as a guiding idea for the next step of the process. The change in form from a passive horn to an ear that can be directed towards sound, for example, directly supports active presence in the world.

These guidelines operated as filtering dimensions (Lim, Stolterman, and Tenenberg 2008) to abductively find resolutions to design problems that were appropriate to the design goals (Kolko 2010b). Sometimes, design ideas came from flights of fancy—the literal ear cemented the idea of listening as well as helped distance the form from a sterile, scientific feel. Other times, as with the design of the memento, concrete iterations around how the design could be made more effective drove the process—from a tech demo with the software library, to self-contained radial forms, to variable-length print representations, and finally to include annotations that locate the memento in a single moment.

Productive tensions as a tool for sensemaking

This paper articulates our efforts and thinking towards creating our desired expression in the aural-visualiser 1000. These include exploring possible means of visualizing sounds, physical manifestations and interactions and continually considering the interplay of these various elements. This interplay has at times induced *productive tensions* that offered us other kinds of expression in the prototype than we expected at the outset.

our prototyping process sought to determine which characteristics best represented an element's purpose (Nelson and Stolterman 2012). One example being the energy capture mechanism evolving from a funnel to an ear. At the same time, the sound memento, a receipt with a waveform on it, might seem "true" in a way that is undermined by the more playful materialisation of the ear that created it. The cartoony qualities of the ear are at odds with the authoritativeness of the aural-visualiser 1000 and the memento it creates. To us, this tension is evocative, and uncovering it through prototyping helped the design progress. The tension creates an invitation to engage with the device—it is not so ridiculous that it can be dismissed nor so serious and scientific that using it feels like a burden to discover something true about the world.

Fallman defines a tension in the dimension between the extremities of design practice and design studies, as the first dealing with what is "real" and the second what is "true" (Fallman 2008). The design became a way for exploring an issue of feeling disconnected by developing a new kind of presence. It was not bound by requirements like solution-oriented design briefs. Still, we found that informing our decisions and aesthetics by imagining the prototype as a "real" appliance (using cues like as scientific visualizations and a retro-technical aesthetic) helped build a stronger expression of the thing, carrying what we thought to be "true"—that people feel disconnected from their surroundings—to show what might be "possible," that listening carefully could foster a sense of presence.

A more prosaic tension lies in the practicality of the materials chosen. As noted in the refinement section, expense led to certain decisions being made on a cost basis. As the goal was to produce a prototype, this was both expected and helpful: infinite resources meant that even fewer constraints would be placed on the project. In keeping with the economic prototyping principle (Lim, Stolterman, and Tenenberg 2008), we feel that this constraint helped us make a prototype that makes the possibilities and limitations of our design idea visible and measurable inexpensively while maintaining high fidelity.

Conclusion: Noticing what is desirable

This paper presented a prototyping process that navigated an open-ended design space. During the design process, various criteria had to be developed to move forward, leading to design questions like *what should the design brief be? Why this and not that? What manifestations of a design idea are relevant? How do you know whether something works?* To answer these questions, a set of intended expressions evolved with the design process that over time made sense of the process. These conceptual expressions, even as they changed, offered perspectives that mattered to design decision-making. They became guiding principles for navigating the design space.

Ultimately, the process of design consists of putting a finger in and seeing what comes out—whether what you have makes sense for a current conception of a project, and whether the prototype or the concept need to change. We identified different tensions and pivots we encountered as essential to this process of composing expressions: knowledge produced during prototyping an expression informs the composing of subsequent expressions. These ideas give us purchase where there were no obviously correct answers and became strategies that helped us attune to what makes a design idea successful. For us, keeping the desired expression at the center of the design process, and paying attention to how attempts to manifest it are supported, thwarted, or made tense offers ways of navigating complex and underspecified design spaces. This is how design is a process of sensemaking driven by articulating desired expressions through prototyping.

Acknowledgements

Thanks to Harvey Bewley and the IxD Lab for advice and support, Peter Nygaard Christensen for photograpy, and finally Thea Emilie Gehrchen, Søren Smedegaard Hansen, and Peter Langgard Pedersen on the project team.

References

Auger, James. 2013. 'Speculative Design: Crafting the Speculation'. Digital Creativity *24 (1): 11–35. https://doi.org/10.1080/14626268.2013.767276.*

Boer, Laurens, and Tom Jenkins. 2021. 'Fostering Creative Confidence with SCD in Interaction Design Education'. Interaction Design and Architecture(s)*, no. 51 (December): 270–302. https://doi.org/10.55612/s-5002-051-012.*

Buchanan, Richard. 1992. 'Wicked Problems in Design Thinking'. Design Issues *8 (2): 5. https://doi.org/10.2307/1511637.*

Candy, Stuart. 2010. 'The Futures of Everyday Life: Politics and the Design of Experiential Scenarios'. https://doi.org/10.13140/RG.2.1.1840.0248.

Dunne, Anthony. 2006. Hertzian Tales: Electronic Products, Aesthetic Experience, and Critical Design*. The MIT Press.*

Dunne, Anthony, and Fiona Raby. 2001. Design Noir: The Secret Life of Electronic Objects*. Berlin: Birkhäuser.*

———. 2014. Speculative Everything: Design, Fiction, and Social Dreaming*. Cambridge, Massachusetts ; London: MIT Press.*

Eklund, Anna, Ulises Navarro Aguiar, and Ariana Amacker. 2022. 'Design Thinking as Sensemaking: Developing a Pragmatist Theory of Practice to (Re)Introduce Sensibility'. Journal of Product Innovation Management *39 (1): 24–43. https://doi.org/10.1111/jpim.12604.*

Fallman, Daniel. 2008. 'The Interaction Design Research Triangle of Design Practice, Design Studies, and Design Exploration'. Design Issues *24 (3): 4–18. https://doi.org/10.1162/desi.2008.24.3.4.*

Gibson, James J. 1977. 'The Theory of Affordances'. Hilldale, USA *1 (2): 67–82.*

Hallnäs, Lars, and Johan Redström. 2002a. 'Abstract Information Appliances: Methodological Exercises in Conceptual Design of Computational Things'. In Proceedings of the 4th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, 105–16. DIS '02. New York, NY, USA: ACM. https://doi.org/10.1145/778712.778730.*

———. 2002b. 'From Use to Presence: On the Expressions and Aesthetics of Everyday Computational Things'. ACM Transactions on Computer-Human Interaction *9 (2): 106–24. https://doi.org/10.1145/513665.513668.*

Kannabiran, Gopinaath, and Susanne Bødker. 2020. 'Prototypes as Objects of Desire'. In Proceedings of the 2020 ACM Designing Interactive Systems Conference*, 1619–31. DIS '20. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3357236.3395487.*

Kolko, Jon. 2009. 'Abductive Thinking and Sensemaking: The Drivers of Design Synthesis'. Design Issues *26 (1): 15–28. https://doi.org/10.1162/desi.2010.26.1.15.*

———. 2010a. 'Sensemaking and Framing: A Theoretical Reflection on Perspective in Design Synthesis'. Proceedings of Design Research Society*, January.*

———. 2010b. ‘Abductive Thinking and Sensemaking: The Drivers of Design Synthesis’. Design Issues 26 (1): 15–28. https://doi.org/10.1162/desi.2010.26.1.15.

Landin, Hanna. 2009. ‘Anxiety and Trust and Other Expressions of Interaction’. Chalmers University of Technology. https://research.chalmers.se/en/publication/92132.

Lim, Young-Kyung, Erik Stolterman, and Josh Tenenberg. 2008. ‘The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas’. ACM Transactions on Computer-Human Interaction 15 (2): 1–27. https://dl.acm.org/doi/10.1145/1375761.1375762.

Maeng, Seungwoo, Youn-kyung Lim, and KunPyo Lee. 2012. ‘Interaction-Driven Design: A New Approach for Interactive Product Development’. In Proceedings of the Designing Interactive Systems Conference, 448–57. DIS ’12. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/2317956.2318022.

Nelson, Harold G, and Erik Stolterman. 2012. The Design Way: Intentional Change in an Unpredictable World. Cambridge, Massachusestts; London, England: The MIT Press.

Norman, Don. 2013. The Design Of Everyday Things. Revised edition. New York, New York: Basic Books.

Padalak, Martin A., and Tom Jenkins. 2022. ‘Being in the World with the Aural-Visualiser 1000’. In Nordic Human-Computer Interaction Conference, 1. NordiCHI ’22. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/3546155.3547281.

Pallasmaa, Juhani. 2012. The Eyes of the Skin: Architecture and the Senses. 3rd edition. Chichester: Wiley.

Pierce, James, and Eric Paulos. 2010. ‘Materializing Energy’. In Proceedings of the 8th ACM Conference on Designing Interactive Systems, 113–22. DIS ’10. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/1858171.1858193.

———. 2012. ‘The Local Energy Indicator: Designing for Wind and Solar Energy Systems in the Home’. In Proceedings of the Designing Interactive Systems Conference, 631–34. DIS ’12. New York, NY, USA: ACM. https://doi.org/10.1145/2317956.2318050.

Rittel, Horst W, and Melvin M Webber. 1974. ‘Wicked Problems’. Man-Made Futures 26 (1): 272–80.

Russell, Daniel M., Peter Pirolli, George Furnas, Stuart K. Card, and Mark Stefik. 2009. ‘Sensemaking Workshop CHI 2009’. In CHI ’09 Extended Abstracts on Human Factors in Computing Systems, 4751–54. CHI EA ’09. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/1520340.1520732.

Russell, Daniel M., Mark J. Stefik, Peter Pirolli, and Stuart K. Card. 1993. ‘The Cost Structure of Sensemaking’. In Proceedings of the INTERACT ’93 and CHI ’93 Conference on Human Factors in Computing Systems, 269–76. CHI ’93. New York, NY, USA: Association for Computing Machinery. https://doi.org/10.1145/169059.169209.

Tharp, Bruce M., and Stephanie M. Tharp. 2019. Discursive Design: Critical, Speculative, and Alternative Things. Annotated edition. Cambridge, MA: The MIT Press.

Martin A. Padalak

Martin is a creative technologist and master's student specializing in interaction design at the IT University of Copenhagen, where he is a design researcher at the IxD Lab. He has a fascination with technology but is skeptical of untamed digitalization and works to develop responsible and sustainable alternatives to contemporary disposable technoculture. He holds a Bachelor of Architecture from the Danish Royal Academy's cross-disciplinary Institute of Architecture and Design. Martin also has theoretical and practical experience with farming, carpentry, student politics, art and graphic design—all of which influence his current work and thinking.

Tom Jenkins

Tom Jenkins is Associate Professor of Interaction Design at IT University of Copenhagen's Department of Digital Design, where he leads the master's specialization in interaction design. He combines research through design with cultural and critical theory to produce speculative electronic artifacts, engaging critically with smart products and systems, and examining how design can produce novel relationships between and among people and devices. He holds a PhD from the Georgia Institute of Technology in Digital Media, a master's degree from New York University's Interactive Telecommunications Program, and bachelor's degree from Cornell University, where he was a member of the Culturally Embedded Computing Group.

Documenting End User Needs in an Interactive Virtual Reality Prototyping Environment for a VR-PD Approach in Architecture

Lukas Adrian Jurk, Institut für Konstruktives Entwerfen, Industrie- und Gesundheitsbau

Abstract

When designing a complex building, such as a hospital, architects have to meet a variety of regulatory and user-centered requirements. With the introduction of participatory methods, architectural design can incorporate end-user requirements, ultimately facilitating end-user processes in the built environment. However, current means of communication, such as paper plans and rendered images, lack the proper form of presentation to discuss, document, and display user requirements, let alone experience the prototype. Often, blueprints, renderings, and animations are not suitable for non-architects to develop a thorough and mutual understanding of the volumes, dimensions, and clearances to assess a design's ultimate usability. A full-scale physical mock-up is usually not feasible. Instead, virtual reality (VR) is sometimes used as a substitute to provide a more realistic impression of the subject under discussion. However, most VR software does not allow for interaction to evaluate the prototypical environment. In addition, neither VR software nor traditional methods are suitable for documenting the results of large-scale surveys without enormous effort. It is usually left to designers to manually document and qualitatively evaluate the results of participatory approaches for a final design decision.

This paper presents a software that could enrich current participatory design methods and overcome their shortcomings. The software's immersive, interactive, responsive, and networked prototyping environment documents design decisions and makes them immediately experiential. An integrated evaluation tool generates a three-dimensional, human-readable representation of the collected quantitative data. Architects can then discuss or integrate the quantitative data with qualitative observation or end-user interview data in a mixed-methods approach. This new prototyping opportunity could lead to a more congruent understanding of communicated imagination and materialized experiential knowledge, while reciprocally generating networked experiential knowledge during its usage. End users could become more like architects themselves.

Participatory Design; Data Triangulation; Architectural Planning; Human Readable Filter; Networked Experiential Prototyping

A thorough understanding of the needs of end users in relation to their environment is key to a user-friendly and sustainable architectural design. This is especially true for complex environments such as hospitals or factories - environments that house many interdependent logistics and work processes of their end users.

Traditionally, architects express and communicate architectural design decisions - or one may say prototypes - by reducing their three-dimensionality into horizontal and vertical sections and projections. These representations are called plans and sections. Typically, the basis for design decisions is sometimes empirical knowledge (e.g., user interviews) and more often literature-based knowledge (e.g., statistics on normative dimensions). Architects and end users express empirical knowledge verbally and document it with pens when discussing a floor plan. However, no empirical knowledge is generated because no one interacts within the floor plan, but only expresses their individual thoughts two-dimensionally. Furthermore, end users are confronted with a specialist medium, the floor plan, which they may not be able to fully decipher due to their often-limited spatial comprehension (Yu et al. 2022). This can lead to misunderstandings and misplanning. The author of this paper has had similar experiences with participatory requirements planning in his own architectural projects.

Virtual reality (VR) technology has revolutionized the way architects and designers approach the design process by overcoming some of these limitations. The ability to create and explore virtual environments allows architects to better visualize and evaluate their designs. It also provides a new way for stakeholders to participate in the design process. Participatory design in virtual reality (VR-PD) is a relatively new field that combines the benefits of VR technology with participatory design methods. Gu et al. found that a three-dimensional representation facilitates more profound perceptual events in collaborative design processes (Gu et al. 2011). However, the currently available tools do not allow for large-scale documentation of quantitative data generated during (asynchronous) collaborative sessions. Furthermore, current prototyping software is not first-person interactive. Thus, designers cannot immediately and immersively experience the consequences of their decisions. In contrast, the developed software allows architects to document, evaluate, and ultimately triangulate quantitative and qualitative data on end-user needs. This enhanced VR-PD can provide architects and designers with a more comprehensive understanding of stakeholder needs.

First, this paper describes the current problems in communicating ideas and comments about an architectural prototype, as well as the shortcomings in empirically validating design decisions during a prototyping phase. Second, it summarizes the potential of using VR. Third, it explains the requirements for successful use of VR, the structure of the developed software and how it meets these requirements. Finally, it describes the proposed design of an enhanced VR-PD approach using the developed software, its potentials, and the need for further research.

The developed software provides a VR prototyping environment that is experiential, transformable, documentable and networked, similar to a beta software environment, eliminating the need for physical mock-ups. Taking, experiencing and evaluating design decisions becomes a simultaneous action. The fundamental question is: How changeable, accessible, experiential and collective can a prototype be? The developed VR software is similar to existing furnishing applications, but extended by the networked ability to document and display survey data for evaluation in a human-readable, three-dimensional representation. It enables the mixing of quantitative and qualitative generated knowledge of end-user needs in complex building projects.

Background

Abstract, Statistical Numbers Transform into Imagined Shapes

Current Methods for Integrating Experience and Needs into Architectural Planning

A central step within the service phase 0 of an architect's work process is demand planning. During this phase, architects collect important data for future planning (DIN18205). The basis of every planning is the functional program (Roth et al. 2015 p.19-20). The data used consists of the documentation of existing processes and procedural knowledge. The intention of the requirements planning determines how the data is collected and interpreted and how statistical analysis approaches are used (Roth et al. 2015 p.36). First, architects determine space requirements based on statistical or experimental metrics before filling the planned spaces with equipment (e.g., surgical lights when designing operating rooms). Planners choose either a bottom-up or a top-down approach, i.e., either to rely synthetically on planning recommendations such as Neufert (Neufert 2018) or Raumpilot (Jocher et al. 2012) or to determine requirements analytically (Roth et al. 2015, p. 37). Common methods include determining space requirements through metrics, functional area surveys, aggregation factoring, and equipment demand assessments. The latter two methods are bottom-up and participatory. They start with detailed planning of equipment and the resulting space requirements for each, its users, and other related processes. Both require empirical values and expert knowledge, usually gathered in expert workshops. In the case of a hospital building project, this may include the involvement of nurses and cleaning staff. In contrast, the first two methods are top-down and numbers-driven. In this case, cardboard pieces - movable and arranged on a grid - represent statistical metrics. This method is exclusive to professional architects and does not take into account the design requirements of the individual work environment, but rather relies on the existence of a high-quality database of benchmarks.

Figure 1-3: Architects can employ various methods when collecting information on user needs. They range from norms to statistical numbers of knowledge of previous inhouse usage, square footage, equipment (e.g., medical technology), logistics and program (space allocation plan) to expert workshops.

Discussing and Documenting Experiential Knowledge: Participatory Methods

Participatory design is a methodology that involves stakeholders in the design process to consider their needs and preferences. This approach has been used in a variety of fields, including architecture, urban planning and product design. Participatory design is effective in promoting stakeholder engagement, improving the quality of the final design, and reducing conflict between stakeholders and designers. According to Leon et al. (Leon et al. 2015), early collaborative design can prevent problems in later, more complex project phases. Architects and end users also benefit from starting to collaborate early in the design phase to innovate and achieve excellent architectural solutions (Combrinck and Porter 2021). This bottom-up approach is particularly useful for requirements and space planning at the detailed design stage. A common method for needs assessment in complex building projects such as hospitals is expert workshops (Sunder et al., 2021). However, there are many challenges with this method.

Using traditional media such as printed floor plans to discuss design decisions for complex building structures with non-architects is difficult. While efforts have been made to involve other disciplines and end-users in previous research projects to meet their needs, the use of traditional media in interdisciplinary communication has been inadequate and prone to communication and interpretation errors. Too often, the expressed experiential knowledge remains a mere narrative, sometimes underscored by drawing on to floor plans or pointing to photos and video sequences.

In addition, it was not possible to document needs on a large scale. This is also evident in other works. According to Alizadehsalehi et al. (Alizadehsalehi et al. 2020), limited understanding of a design decision can lead to poor design choices. Sometimes planners compensate for the shortcomings of this form of communication by undertaking time-consuming work experiences in facilities comparable to their design task. All in all, the mental images of architects and stakeholders are traditionally expressed and discussed in a two-dimensional or verbal way, but not experienced.

Potentials of Virtual Reality

Current Usage of Virtual Reality in Prototyping

Traditional methods of reviewing architectural prototypes are confined not only in space, but also limited in their temporal dimension. Therefore, a common method for process optimization is simulation. However, the extent and level of detail and realism is highly dependent on the means of simulation (Roth et al. 2015). While physical mock-ups are quite expensive, immersive virtual environments (ImVE) have been widely used in recent years. The ability to create and explore virtual environments has allowed architects and designers to better visualize and evaluate their designs. It can be used to test the feasibility of a design and identify potential issues. The combination of VR technology and participatory design (PD) methods has led to the development of Virtual Reality Participatory Design (VR-PD). VR-PD allows stakeholders to participate in the design process by exploring virtual environments and providing feedback on the design. At the same time, the concept of Computer Supported Cooperative Work (CSCW) has evolved, exploring, among other things, cooperative VR applications. The fully immersive experience of a virtual prototype viewed through a head-mounted display (HMD) enables a new level of visualization and perception of design decisions, but more importantly, fundamentally changes the designing of prototypes themselves. Ververidis et al. identify five benefits of VR: interactivity, spatiality/three-dimensionality, immediacy, telepresence, and simulation (Ververidis et al. 2022, p. 478). Therefore, architects can collaborate in virtual reality with more comfort and ability (Yu et al. 2022). Various sources demonstrate that VR, can be a more inclusive tool for end user engagement by raising information on performance feedback (Heydarian et al. 2015). This immediacy is one advantage of the developed software later described in this paper. In addition, the VR medium has a higher level of detail and dimensionality, leading to easier perception and communication of mental ideas. Therefore, on the architect's side, ImVE can facilitate the process of problem finding (Lee et al. 2019). According to Ververdis et al. VR should ideally enable communication, visualization, documentation and record keeping. In addition, all stakeholders should be able to "converge in a single experiential space" in a synchronous and asynchronous manner (Ververidis et al. 2022, p. 491). VR and collaborative approaches are two mutually reinforcing factors that facilitate communication between planners, stakeholders and end users.

Prospect of Becoming an Actor of Iteratively Manifesting Knowledge

As an ideal framework for collaborative design, Ververidis et al. propose an iterative process in which design decisions are immediately made, previewed, and reviewed. In doing so, the parallel worlds of different stakeholders must intersect (Ververidis 2022, p.491). Embodied designing within ImVE enables this triad by changing the traditional central meaning of models or prototypes from the anticipation of a future construction to the process of design itself (Reinfeld 2021). Five factors are critical to realizing these potentials of VR:

1. *Multidimensionality*: VR has the advantage of adding a third life-size dimension to scaled printed floor plans, and a fourth dimension by spatiotemporally immersing the user. One can now experience the realistic duration of walking through a design instead of moving a pen across a piece of paper.
2. *Visual Infinity/Immersion:* The technical impossibility of stepping back from the image plane, as well as the seemingly infinite virtual image of the HMD without an image border, redirects visual perception towards immersion (Wiesing 2014: 107-108). This advantage becomes apparent when comparing ImVE with the perception of the limited size of a printed floor plan.
3. *First-Person-Interaction*: The first-person user interface allows the user to interact with an interface and environment as they would with that of a real-world object. It ensures correctness of ergonomic results and the comprehension of dimensionality of the virtual space. Only then, can the assessment be close to a realistic work process.

4. *Dialogical Interactivity:* The user-designer no longer has to interpret the design decision through the abstraction of a drawing (Drude 2023, p.10). Instead, the users can immediately react and experience to their own virtually realized design to make new decisions.The prototype develops, not evolves, as design is a real-time dialog. According to Drude, multi-user VR applications can enhance communication between participants that was previously inhibited by relying solely on sketching and model making (Drude 2023, p.11). Others also point to the enhanced visualization and immediate interactivity of ImVE (Rahimian et al. 2019).
5. *Iterative Immediate Experience of Action:* Once mobilized, users can immediately experience the consequences of their own virtually realized design. The user-designer no longer has to interpret the design decision through the abstraction of a drawing (Drude 2023, p.10). Instead, the user can immediately react and experience the transformed virtual prototype in order to make new decisions.

The VR-Software and its requirements

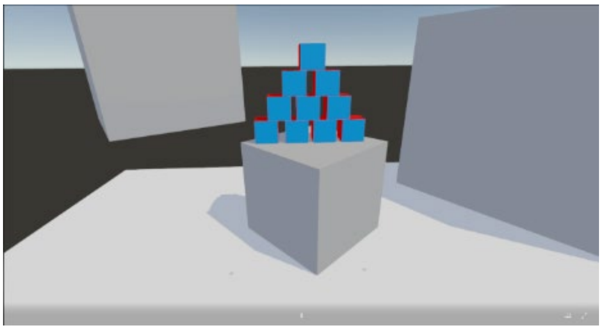
The proposed enhancement of VR-PD employing the developed software aims to overcome the cognitive, communicative and media-related problems of traditional participatory design processes in architecture and interior design for complex building structures such as hospitals. By challenging these limitations and building on the potentials of virtual reality and data collection, an enhanced VR-PD approach is proposed. The software described in this paper enables end users and architects to simultaneously create and experience prototypes in a realistic first-person interaction. Live-sized virtual objects, walls, doors and windows can be placed and moved. Furthermore, the networked prototyping software automatically documents decision data quantitatively and qualitatively for an evaluation of large-scale datasets. It transforms collective experiential knowledge into virtually materialized and augmented environments.

However, the medium of VR requires certain elements for an optimal operability. Ververidis et al. propose several features of an ideal software based on their review of collaborative VR systems for the architecture, engineering and construction (AEC) industry (Ververidis et al. 2022). The developed software incorporates some of these features and adds others. A HP Windows Mixed Reality Headset, its two controllers and first-person interaction are employed.

General Requirements of Optimal Operability

Familiarization with Virtual Reality and Sensory Discrepancy

The sensation of immersion in first-person interaction may be overwhelming for first-time users (Sidani et al. 2021). The software and hardware do not provide auditory or olfactory feedback, but only visual and limited haptic feedback. In addition, users cannot physically sense virtual stairs when moving in a planar real space. These discrepancies can lead to discomfort and should be limited and addressed in the design of the virtual environment. Therefore, the interviewer must first instruct the users about the expected irritations, teleportation features and controls. The developed software includes a training environment that prepares users for the actual use.



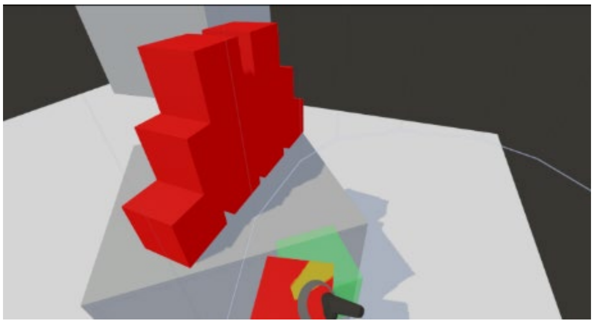


Figure 4-5: Visually simplified training environment for users to familiarize themselves with controls and features before starting the actual survey of the VR software

Techno-Spatial Restriction and the Mobilization of the Self-Aware Designer

Simulating realistic behavior in an ImVE requires commitment on the part of the interviewee and a comfortable rapport, as there are spatial and physical inhibitions. The user must understand the importance of becoming physically active. Otherwise, the exploration of the virtual space fails and the user remains a mere observer of a rendering. Mobilization is the key to the full expression of the imagination. Only then does the media relationship between space and image become physical. In addition, the user must understand the HMD as a drawing tool to not only observe the environment, but to create life-size designs within it (Reinfeld, 2021). The physical barrier of a tethered HMD or tracking space limits the user's ability to move further into visual infinity. The resulting teleportation feature of ImVE limits the realistic spatial and temporal experience of virtual space - just as the dimensions of a traditional paper floor plan would limit the space for imagination to an even greater extent. An engaged, self-aware user, on the other hand, achieves a level of engagement and immersion previously unknown.

User Interface of the ImVE

Preset Options and Object Library

The software requires the definition of an object library prior to conducting interviews. Standard CAD files can be imported for room and object geometry. Before each survey, its scene(s) can be selected by choosing a specific room (e.g., a two-bed patient room), a specific furnishing preset (e.g., two patient beds and chairs), and a light setting (e.g., nighttime). Depending on the design stage being discussed and how open-ended the process should be, interviewers can set more or less presets and restrictions to the interviewee's design freedom to build and react upon (e.g., just two walls and a bed or a fully furnished room layout). Multiple scenes can be set sequentially or in random order to avoid bias. Furthermore, a selection of available objects can be set for the interviewee's object library within the ImVE.

Navigation Simplicity

User-friendly controls are critical to smooth operation. The primarily gesture-based software controls require only a forefinger press for all grasp-like decisions. All other commands are intuitive and require realistic interaction (e.g., using a doorknob to leave one scene and enter the next virtual room). However, the controller does restrict the user's hand pose and movements to a certain extent.

Placement and Deletion of Objects

Ververidis et al. suggest optimal usability of a toolbar by placing it on the left VR controller while using the right controller for selection commands (Ververidis 2022, p.489). All objects are virtually located on the left forearm and can be scrolled through in a left-right and up-down movement of the right hand. They are grouped into categories for easy navigation. Once selected with the right controller, an object is scaled to life size and can be placed in the ImVE. The interviewee becomes not only the bearer of the ideas and knowledge being expressed, but also the bearer of the virtual objects.

The virtual placement of objects should be as close as possible to the actual morphology of the interviewee to achieve optimal ergonomic design review results. A common problem is the imprecision of freehand VR designing compared to numerical input placement in CAD software. So, there are support mechanisms. Auto-snapping places an object on the wall at the height of the user's controller. It locks the z-axis when placing objects on the floor or ceiling. Autorotation snaps the module or object to the target plane orthogonally away from it. Deleting misplaced objects requires grabbing them, dragging them to the library area on the left forearm - which instantly becomes a trashcan icon visually - and dropping them.

Figure 6: Library with scaled down objects at the user’s lower-left forearm. One can scroll through the library by gesturing with the right-hand controller and pick a desired object for placement.

Figure 7: The software suggests a green highlighted snapping position to a user placing a socket on a wall.

Figure 8: A user drops a misplaced dispenser in the bin to delete it.

Individual User Evaluation

After equipping a scene to their needs, the interviewees can test and correct their design decisions in four ways within the ImVE:

1. *Light Setting:* Different times of the day and different work processes require different light settings. For example, a doctor needs pure white light to see a patient's skin color without distortion. Cleaning staff, on the other hand, need a full and bright illumination of the room. Therefore, different light settings can be shown to evaluate the usability of a room under different light conditions.

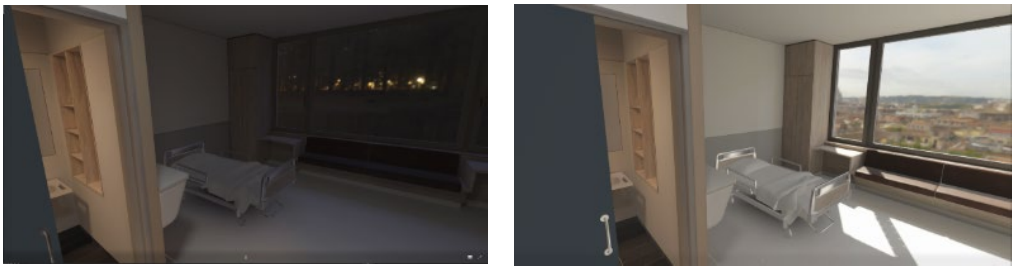


Figure 9-10: An exemplary daytime and a nighttime light setting of the same space.

2. *Prioritizing:* Although end users may prefer the placement of many objects, financial or regulatory constraints may prevent the implementation of all design decisions. Therefore, users can highlight important objects by selecting the star that hovers over an object.

Figure 11-12: A user highlights a wall socket.

3. *Area Sizing through Collision Feedback:* A common case of misplanning is the incorrect sizing of areas. Thus, interviewees can test for spatial flaws, as all virtual objects resemble physical properties. For example, a patient bed requires the use of both controllers and has

sluggish motion properties to represent a realistic weight. Other objects may have dimensionally restricted joints or cannot float in mid-air. When moving objects, collisions are indicated visually by red spheres briefly emerging at the point of collision and haptically by vibrating controllers.

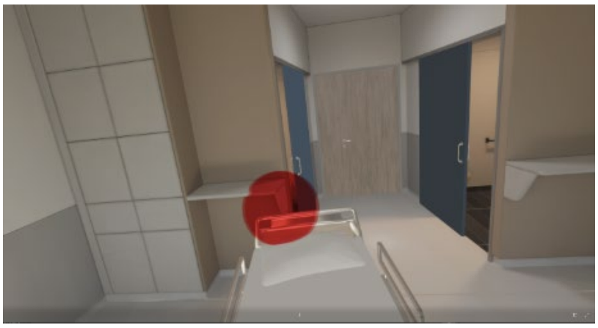


Figure 13: A point of collision flashes with red spheres.

4. *Walking Pattern:* The right distancing between places of action is essential to user-friendliness. Stakeholders can neither walk through a displayed rendering nor a scaled paper floor plan. The empirical knowledge generated by truly walking through a prototype is only possible in ImVE or within a physical mock-up. The software visually indicates when a virtual obstacle is approached too closely by blending in a grid that resembles a chain-link fence. This allows users to test the distance between points of interest in their design.

Figure 14-15: Virtual wall or obstacle at distance and a grid mapped on top of the obstacle when approaching it too closely.

Evaluation Tool for the Interviewers

The core novelty of the developed software is its ability to save user and prototype related quantitative data for evaluation and mixing with qualitative data in a database. This information can be filtered, displayed and reviewed in a three-dimensional, human readable form. Afterwards, it can be mixed with qualitative data for triangulation. The collected data include: *Interviewee Related:* Occupation, department (e.g., neonatology, assembly line), age, height, years of work experience; *Survey Related:* Date, time, number, duration, selected scenes (rooms, light-setting, object preset); *Object Related:* Type, absolute and relative position, ergonomics, number, prioritization

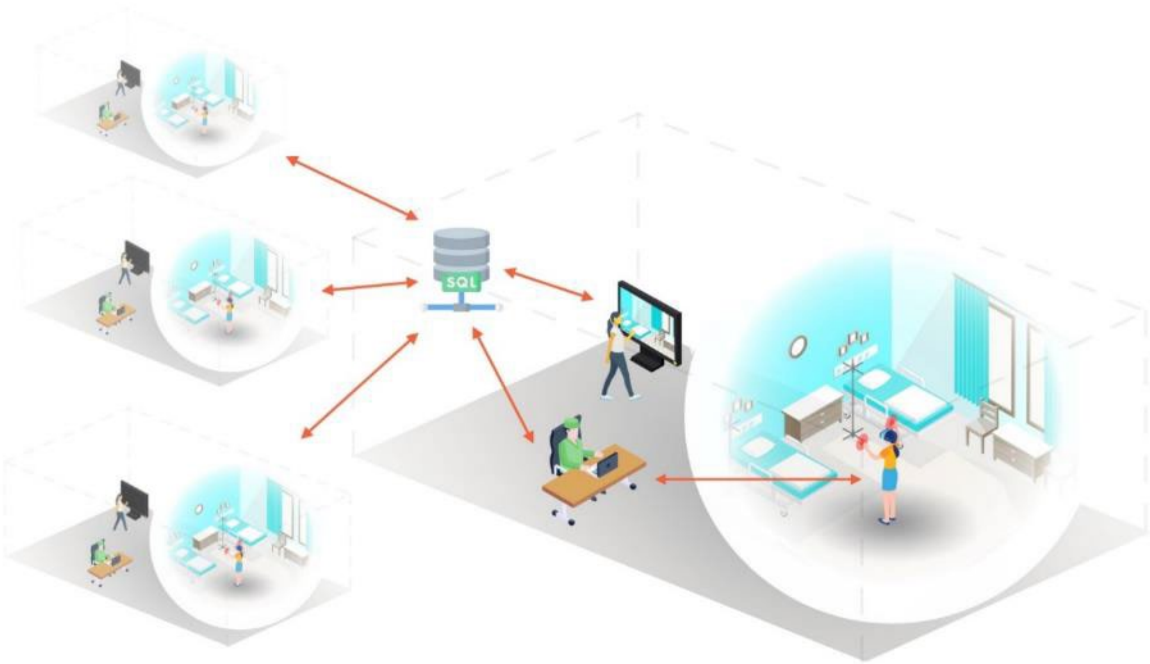


Figure 16: The software centrally documents the design decisions of all interviews on a database, while interviewers can conduct and evaluate interviews (a-)synchronous and location-independent.

At first, the evaluator’s GUI provides many filtering options: e.g., populations of the survey (e.g., show all, hygienists and caretakers), categories of objects, personal data (e.g., height). Two visualization modes of the results are available - a heat map and a scatter plot. A split screen can simultaneously display both modes and four camera perspectives. Exploring results can be experientially conducted in first-person ImVE or more traditionally on a screen. A blue to red gradient color coding indicates the averaged, collective information of ideal object arrangement in the heatmap mode in a human-readable way. Blue indicates that the filtered population did not place any object at that location. Red signals the location(s) with the most placed objects of the filtered population. The gradient in between signals less frequently selected locations. The scatter plot mode indicates which type of a particular object was selected at each location, or helps distinguish between selected objects when more than one object category was selected in the filter options. In this way, large survey sets can be made accessible, readable, and discussable.

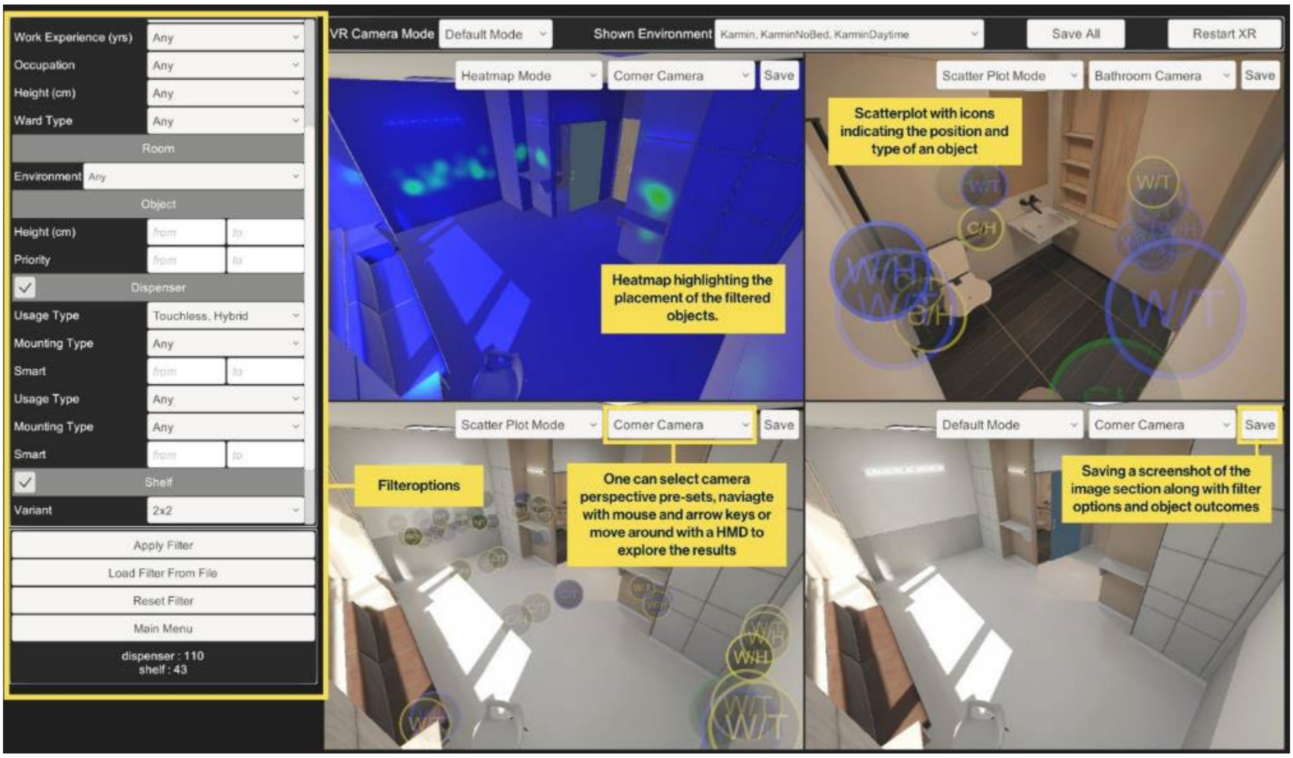


Figure 17: Overview of the evaluation interface with explanations in yellow

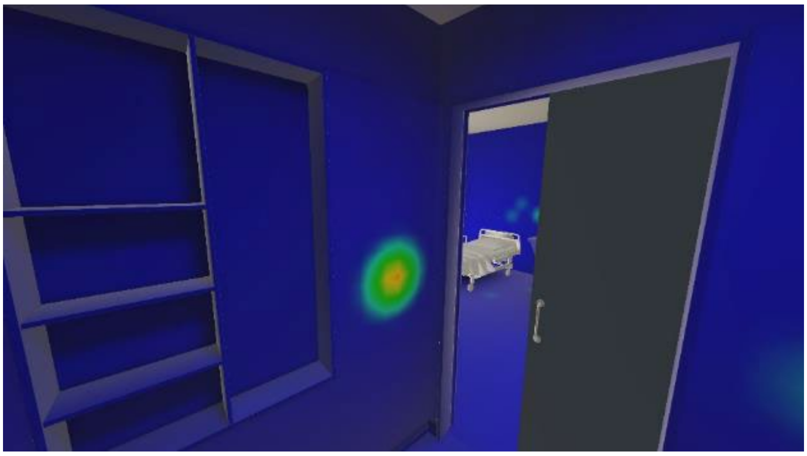
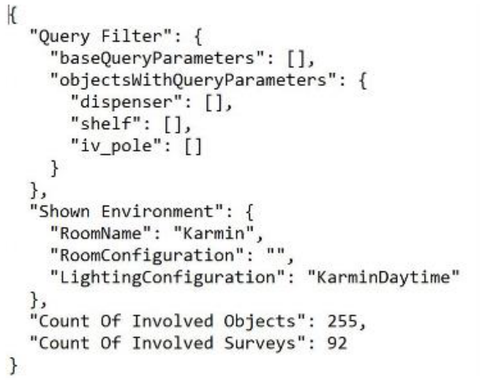


Figure 18: Example of the heatmap visiualization mode within ImVE

Screenshots

Taking screenshots enables planners to document issues or findings that require further discussion. For this reason, the evaluation tool includes a screenshot button to export a visualization of specific filter results in the desired presentation mode (rendering, heatmap, scatterplot) and camera perspective. The software also numerically saves the selected filter settings and associated database output along with the screenshot.




```
{
  "Query Filter": {
    "baseQueryParameters": [],
    "objectsWithQueryParameters": {
      "dispenser": [],
      "shelf": [],
      "iv_pole": []
    }
  },
  "Shown Environment": {
    "RoomName": "Karmin",
    "RoomConfiguration": "",
    "LightingConfiguration": "KarminDaytime"
  },
  "Count Of Involved Objects": 255,
  "Count Of Involved Surveys": 92
}
```


Figure 19-20: Example of a screenshot with scatter plot of a filtered survey result along with the underlying data. Planners and researchers can use both for further evaluation and discussion.

Heat Map Evaluation Algorithm

The heatmap mode can display large datasets in a human-readable way visualizing end user needs. Heatmaps are created by dividing the space into 3D pixels. The level of detail can be modified according to how precisely the position of an object needs to be determined. One pixel in the shown screenshots is equivalent to 8x8x8 cm. The evaluation tool calculates the color value according to the distance of the filtered objects (e.g., a dispenser) to a 3D pixel using the following graph. Distances of an object to a 3D pixel exceeding 0.3m are ignored.

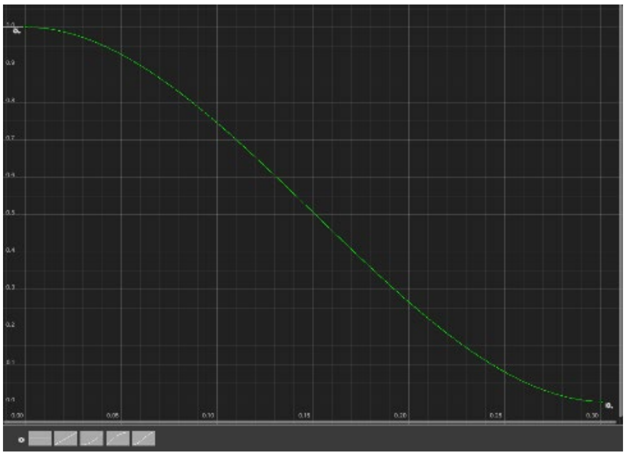


Figure 21: Graph for assigning the color value of a 3D pixel: the x-axis indicating the distance from the 3D pixel to the object position in meter, the y-axis the assigned color value.

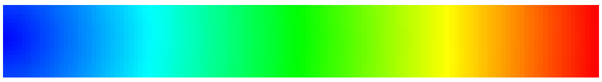


Figure 22: The heat gradient has the value 0 (blue) on the left and the value 1 (red) on the right.

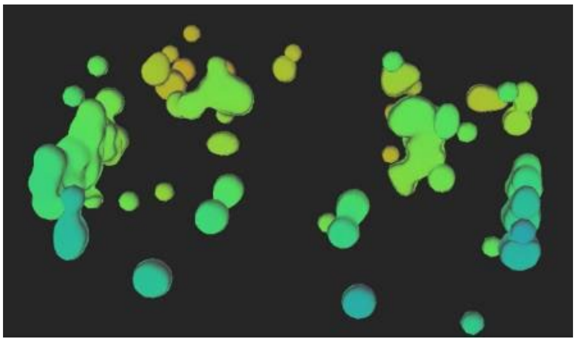


Figure 23: Visualized 3D example of the total amount of colored 3D pixels of an evaluation sample.

After assigning and adding the color values, the algorithm divides the sum of each 3D pixel value by the sum of the highest value pixel. The pixel with the closest objects will therefore have a value of 1, which corresponds to a red coloring. 3D pixels with a lower value have a corresponding color gradient. Pixels with no nearby objects have a color value of 0, which corresponds to a blue coloring. Finally, the algorithm maps all 3D pixel color values to the room and object surfaces of the underlying 3D models to visualize the data in a human-readable manner. In contrast, the scatterplot mode is not well suited for displaying averaged data of end user needs Evaluators benefit from using it when they want to distinguish between object types. A mode for exporting a CAD file of an ideally furnished room is under development.

The Potential of Networked VR-PD Prototypes

Ververidis et al. point out that central server communication is critical for retrieving, reviewing, and editing information at any time (Ververidis et al. 2022, p. 486). Participating experts and end users become a source of data immediately responding to their own realizations and expressed knowledge in ImVE. In addition, they also become quantitatively shaping parts of the aggregation of networked design decisions. Researchers, planners, and stakeholders can evaluate survey results of the network (including other projects) documented on a database to gain insights and identify shortcomings in their planning. These findings can be further enriched by integrating them with qualitative data from observations and interviews conducted during the participatory designing in ImVE. Insights can then be generalized.

Proposed VR-PD Approach

The traditional PD-approach may use qualitative and/or quantitative data as previously mentioned. However, these data are usually not derived from a specific design context. On the contrary, the newly proposed approach enriches VR-PD by enabling data triangulation. This data integration combines many individual advantages possibly leading to a higher reliability of the results of architectural PD-processes.

Advantages of Quantitative Methods	Advantages of Qualitative Methods
Reaching a large number of people	Respondent has influence on content
Representative results	Feedback can be expressed directly
Statistical evaluation of results with comparatively little effort	Flexible and open methodology, therefore also the new and unknown is recorded
Statistical correlations can be determined and mapped	Possibility of reaction
Subjectivity is reduced as far as possible	Positive influence on data quality or respondent motivation

(Lehnen 2017)

Small, internal trials of the proposed VR-PD approach have been conducted at IKE, TU Braunschweig for a hospital architecture project. Its feasibility will be further tested during a large architectural planning process for a major university hospital in Europe this summer. A defined procedure has to be followed:

1. Take Decision on Setup and Evaluation Objective
2. Undertake Survey According to Protocol
3. Conduct Evaluation and Final Design Decision

Take Decision on Setup and Evaluation

The way the software is used should depend on a project's design stage determining the prototyping and evaluation objective. Scene setups can differ in the degree of participatory input ranging from building an entire room structure to furnishing and/or testing spatial dimensions of a preset room layout or light setting. Is a single room or a cluster of rooms to be discussed for process assessment? The first step is to determine the set. The evaluation should also consider the need for contrasting opinions from end-user groups (e.g., practicing caretakers and theoretically working hygienists). An interviewer should define a specific task for the invited stakeholders or develop an interview guide to set incremental tasks depending on these objectives.

Undertake Survey According to Protocol

First, the interviewee needs to be instructed on the task. Then, the interviewer needs to familiarize the interviewees with VR, its controls and limitations using the training environment of the software and ensuring equal preconditions to all interviewees. Once the survey has started, the interviewee should begin designing. The interviewer can facilitate this performance by setting activating tasks to overcome the techno-spatial limitations.

Towards the end, the interviewee should be reminded to review, highlight and test their own design decisions and may begin to redesign or make changes. In this way, users can virtually materialize abstract ideas to generate knowledge. However, the seemingly effortless availability of virtual objects may encourage excessive placement of wishes rather than needs. The possibility of deleting objects should be mentioned ahead of completion of the survey. Meanwhile, qualitative data can be recorded by writing down key messages or answers to the interview guide.

Conduct Evaluation and Final Design Decision

The evaluator will decide whether to compare individual surveys or sets of surveys from different populations (e.g.; caretakers and hygienists) or evaluate the averaged totality of surveys. Qualitative and quantitative data should be integrated at this point to take final design decisions or go into a discussion if results are contradictory or ambiguous. Also, a new setup for a new survey can be determined based on the evaluation results if a specific prototype condition is to be verified.

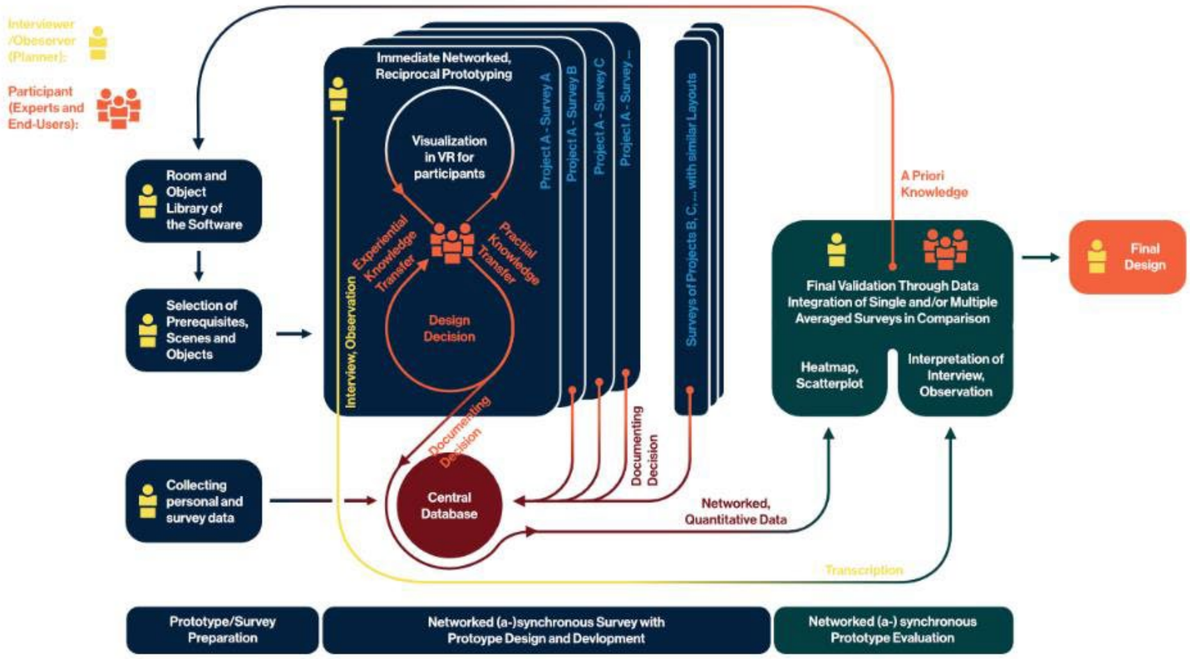


Figure 24: A diagram of the enhanced VR-PD approach for recursive experiential prototyping

Figure 25: Artistic representation of an already conducted prototyping session for a patient room design using the developed software at Institut für Konstruktives Entwerfen, Industrie- und Gesundheitsbau, TU Braunschweig.

Discussion and Future Research

The proposed networked, virtually experienceable prototyping approach can facilitate participative and collaborative requirements planning. It does so by providing the means to concretize, visualize, and experience design decisions close to reality to generate concrete design decisions. Combining qualitative and quantitative data in a mixed method approach can lead to designs that are more reliable. Ultimately, designers can use the tool to create sustainable and complex architecture. However, the method does not anticipate future technological and social developments that may change user needs. The described approach is time-consuming and does not take into account the demographic evolution of its users. Planners can address these limitations to some extent by researching whom to invite before using the software and by incorporating technological advances into the virtual object library of the software. The power of its database and averaging evaluation tool unfolds when large data sets of similar room typologies are merged. Bilinear interpolation of the 3D pixels could lead to a more precise readability of the generated heat maps. In addition, it remains to be determined which color gradient is more readable for the evaluators. Further research is needed to determine the necessary level of detail, the impact of surface color choices on user attention and how to address beginners’ difficulties in getting started with VR.

Feedback from using the proposed approach during a large architectural planning process for a major university hospital in Europe will lead to improvements this summer.

Conclusion

Internal trials of the software and methodology with (non-)architects indicate that VR-PD is an effective approach for involving stakeholders in the design process and ensuring that their needs and preferences are taken into account. Stakeholders were able to provide valuable feedback on the design, which allowed the architects and designers to refine and create a final design that reflected the stakeholders' needs and preferences.

The virtual prototype can become an ever-changing discussion piece made up of the realized individual imaginations. It virtually materializes collective knowledge. Planners can combine the insights of continuously evolving experiential spaces with those of simultaneously recorded narratives. Because of the unprecedented power of the quantitative evaluation tool, mixed data can lead to a more precise design decision than traditional collaborative methods. In addition, planners can potentially use the approach to redesign and evaluate virtual copies of existing spaces that are in use and therefore physically inaccessible (e.g., an occupied assembly line). Possible applications of the approach could be interdisciplinary research requiring a high level of visualization for knowledge communication and especially the AEC industry.

References

Alizadehsalehi, S., Hadavi, A. and Huang, J.C. (2020). From BIM to extended reality in AEC industry. Automation in Construction, 116, 103254.

Combrinck, C. and Porter, C.J. (2021). Co-design in the architectural process. Archnet-IJAR, 15, 738–751.

DIN 18205 (D) st VÖ nach Lützkendorf.

Drude, J.P. (2023). Vom Reißbrett in die Virtuelle Realität: Wie sich unsere Entwurfsperspektive verändert.

Gu, N., Kim, M.J. and Maher, M.L. (2011). Technological advancements in synchronous collaboration: The effect of 3D virtual worlds and tangible user interfaces on architectural design. Automation in Construction, 20, 270–278.

Heydarian, A., Carneiro, J.P., Gerber, D., Becerik-Gerber, B., Hayes, T. and Wood, W. (2015). Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. Automation in Construction, 54, 116–126.

Jocher, T. and Loch, S. (2012). Raumpilot Grundlagen Institut Wohnen und Entwerfen, Universität Stuttgart. Edited by Wüstenrot Stiftung. Eine gemeinsame Veröffentlichung der Wüstenrot Stiftung und des Karl Krämer Verlags, Ludwigsburg/ Stuttgart.

Lee, J., Kim, J., Ahn, J. and Woo, W. (2019). Context-aware risk management for architectural heritage using historic building information modeling and virtual reality. Journal of Cultural Heritage, 38, 242–252.

Lehnen, J. (2017). Integration von Lead Usern in die Innovationspraxis. Forschungs-/ Entwicklungs-/ Innovations-Management, Springer Fachmedien Wiesbaden GmbH.

Leon, M., Laing, R., Malins, J. and Salman, H. (2015). Making collaboration work: Application of A conceptual design stages protocol for pre-BIM stages. WIT Transactions on Built Environment, 149, 205–216.

Neufert, E. (2018). Bauentwurfslehre Grundlagen, Normen, Vorschriften. Springer.

Rahimian, F.P., Chavdarova, V., Oliver, S., Chamo, F. and Amobi, L.P. (2019). OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing. Automation in Construction, 102, 1–16.

Reinfeld, P. (2021). This is Real. Architektonisches Entwerfen in Virtual Reality. In: Wolkenkuckucksheim | Cloud-Cuckoo-Land | Воздушный замок, International Journal of Architectural Theory (ISSN 1430-3863), 25. Jg., Nr. 40, Mediale Praktiken des architektonischen Entwerfens, 93–110.

Roth, C., Dombrowski, U., & Fisch, M. N. (2015). Zukunft. Klinik. Bau. Strategische Planung von Krankenhäusern. Springer Vieweg Wiesbaden.

Sidani, A., Dinis, F. M., Sanhudo, L., Duarte, J., Santos Baptista, J., Poças Martins, J., & Soeiro, A. (2021). Recent Tools and Techniques of BIM-Based Virtual Reality: A Systematic Review. Arch. Comput. Methods Eng., 28, 449–462.

Sunder, W., Moellmann, J., Zeise, O. & Jurk, L. A. (2021). Das Patientenzimmer – Planung und Gestaltung. Birkhäuser, Basel

Ververidis, D., Nikolopoulos, S., & Kompatsiaris, I. (2022). A Review of Collaborative Virtual Reality Systems for the Architecture, Engineering, and Construction Industry. Architecture, 2, 476–496. https://doi.org/10.3390/architecture2030027

Wiesing, L. (2010). Fotografieren als phänomenologische Tätigkeit. Zur Husserl-Rezeption bei Flusser. In Flusser Studies. Multilingual Journal for Cultural and Media Theory. Ausgabe 10, 1-9. Retrieved from http://www.flusserstudies.net/sites/www.flusserstudies.net/files/media/attachments/wiesing-fotografieren.pdf

Wiesing, L. (2014). Artifizielle Präsenz. Frankfurt a. M.

Yu, R., Gu, N., Lee, G., & Khan, A. (2022). A Systematic Review of Architectural Design Collaboration in Immersive Virtual Environments. Designs, 6, 93. https://doi.org/10.3390/designs6050093

Lukas Adrian Jurk

Lukas Adrian Jurk is an industrial and social designer who studied at the Braunschweig University of Fine Arts, architecture at the Universidad de Chile and social design at the Design Academy Eindhoven. Already in the context of his bachelor thesis he dealt with design in the hospital context.
He currently works as a research assistant at the Institute for Constructive Design, Industrial and Healthcare Construction (IKE) at the TU Braunschweig, Germany. There, he has already researched interactional and structural infection prevention measures as well as methods of patient education in patient rooms in the SAVE project and previous projects His work also includes the development of infection prevention devices and the management of the Institute's Innovation Lab. He develops virtual and augmented reality applications for AEC workflows.
He is also a consultant for infection preventive buildings, a member of The Complicity collective since 2020, and exhibits his freelance biodesign work in international exhibitions.
"Making the unrecognizable tangible" is his guiding principle when it comes to exploring the interplay between static, inorganic building mass, objects and the organic inner life from the scale of humans to microbes in relation to health, biological processes and behavior.

Conflicts of Interest: the author declares no conflict of interest.

New patterns of prototyping: developing concepts with playful exploration and probing. A case study within arts and design.

Michael Johansson, Hochschule Bonn-Rhein-Sieg University of Applied Sciences, Germany
Andreas Siess, Kristianstad University, Sweden

Abstract

This paper explores the initial phase of a series of prototype-based design investigations in the field of visual and interactive computing from an artistic and design-oriented perspective. We propose a novel paradigm for interacting with prototypes, particularly suited for the contexts of design and art. Accordingly we demonstrate how this interaction, referred to as “probing”, differs from the traditional approach of prototyping (i.e. experimenting). These findings are exemplified and illustrated by an actual prototype that is presented alongside. By introducing this prototype, which can be understood as an artistic framework, we derive a model that systematises the creative work with and on prototypes into an epistemological typology. Through this “probing” we come to realise the importance of embracing and utilising the quirks, flaws and limitations that arise, which can become prominent features of the design with unique qualities. Finally, we provide insights and a model how these concepts can be applied to prototype-based design and development in general.

Art & Design; Probing; Playful Interaction; Transformational Stepping

This paper examines and gives insights into and examples of the early stage in a series of prototype-based design explorations in visual and interactive computing from an artistic and designerly perspective. With our background in art, computer animation and 3D modelling, we wanted to challenge and explore how our knowledge, professional experience and artistic intent could be organised and constructed in a co-creative dialogue centred around a concept of a machine which, through its construction, could ensure desirable yet surprising outcomes. Thus, through co-creation, we could learn and reflect upon the virtual and the physical simultaneously. We use the concept of a potential machine to find out if we can become cartographers, explorers and painters at the same time (Olsson 2007) as we design the machine itself. In this paper, we want to show how 3D objects, movement and light sources can facilitate new forms of image and map-making, through a series of transformational steps mediated as a shadow world and captured on a white surface. From previous projects, we highlight the importance of making use of the quirks, errors and shortcomings that constantly appear (Siess et. al 2019) and that—if used smartly—can become major features of the design with specific new qualities. “We must integrate the element of the unknown into the design process as a constitutive, productive factor for design—not simply as a lack of data, but as a driver of design development." (Folkmann 2014) The paper presents a model of how our prototype work is executed and includes examples and findings. We also show two case studies of the preparation for the second iteration of the machine prototype. They were created as an installation piece for the *Evangelische Stadtkirche am Marktplatz* in Karlsruhe, Germany and a project that generates real-time music performances from shadow maps by interpreting them as a "music score".

The difference between simulation and virtuality

At this point, we would like to pose the question of whether a prototype should always be interpreted as a simulation, or whether it is also a suitable source of inspiration. To clarify: The goal of a simulation is to replicate "physical" (i.e. "real") phenomena as accurately as possible. Therefore, simulation strives to create objects that pretend to be their "real" counterparts (Esposito 1998: 270). Our prototype, on the other hand, does not pursue this goal at all, but literally turns this relationship on its head, since it is not intended to reproduce the real world, but rather to serve as an inspiration for the generation of ideas which, in turn, will then have an impact on physical reality. In the late 1990s, this difference had already been extensively addressed—albeit in a completely different context, i.e. in the distinction between simulation and virtuality. We would now like to argue that the ontology of the prototype cannot be read in the context of simulation exclusively—in which it undoubtedly provides valuable contributions to the very practice of design—but can also be interpreted in the context of the virtual and thus be used for (visual) arts as well. The virtual, as Esposito or Ryan note, pursues much richer intentions than simulation, but seeks to create genuine transformative qualities for which the question of a "real reality" is completely indifferent (Esposito 1998; Ryan 2015). Accordingly, the key question is not whether a prototype can represent a real phenomenon as accurately as possible, but rather whether a prototype significantly impacts the interacting artists/designers to empower them in their endeavour to reshape reality. Much like the proverbial oak in the acorn—a quote erroneously attributed to Aristotle—the prototype only plants the "seed", from which, depending on the context and especially on the interacting subject, a new (proverbial) tree grows (Lévy 1998). Thus, the prototype, or virtual model, serves as a starting point for the development of new ideas and ways of understanding the world. Since it is not concerned with accurately reproducing reality, but rather with empowering the artist or designer to shape and reshape reality in meaningful ways, it demands new paradigms of interaction that embrace and "exploit" the ambiguity and plurality of the prototype. Schiesser conceptualised this characteristic of a medium using the term *Eigensinn*, which can be roughly translated as "obstinacy" (Schiesser 2004). This term conceptualises the "drive" of any artistic material (i.e. in our case, the prototype) for certain aesthetics, mechanisms and functions in constant interaction with the obstinacy of the interacting subject, creating a "force field" between subject and prototype that initialises and nurtures the creative process. Since any creative process could benefit from transformational qualities that forsake the ideal of replicating external circumstances as faithfully as possible (Ryan 2015), we believe this brief discussion of the virtual vs. simulation resonates with the new paradigm of prototyping that is presented in this paper. It is important to emphasise that the virtual is not necessarily synonymous with the digital (Lévy 1998). Thus, a physical prototype can possess virtual qualities if it features genuine transformative characteristics and deviates from the ideal of simulation.

Models of creativity for supporting collaborative prototyping

To establish a common ground regarding ideas and models of creativity, we gathered four different models of creative action. They all serve our online collaboration with concepts, terminology and perspectives that help us shape the collaborative space between us as we generate, elaborate, and evaluate concepts regarding our prototyping with the machine. We believe that this methodological perspective is necessary to collectively develop and use different ways of thinking and analysing creative practice.

Ruth Knoller conceptualises creativity in a comprehensive "formula", in which creativity (C) emerges as a function (f) from knowledge (K), imagination (I) and evaluation (E), as well as a positive attitude (a) as a key part in the equation: C=fa(K, I, E) (Isaksen 2011).[1] How can a machine's attitude (i.e. its *Eigensinn*) be designed and explored, in order to push knowledge, imagination and evaluation into play? Furthermore, we wanted to address Boden's idea about "conceptual space": How can prototypes be set up to host conceptual spaces that can be explored, stressed, and played with spatially? Finally, Yuk Hui's ideas regarding autofinality (A-B-C-A) come into play, since in a creative process "the result is not yet completely defined: even finality itself is situational" (Hui 2019). How do we specify and design the rules that determine computational behaviour and how do you become aware of the details of the computer system that interprets such rules? To avoid that the technological systems become self-contained and self-referential, limiting the potential for artistic intervention and creativity.

The prototype

Key inspirations

For inspiration and reference to the mechanism and layout of an interactive and procedural machine, we initially turned to three different sources as our starting points:

1. "Wheel" by M. Tansey and F. Buener (Taylor/Tansey 1999)—an analogue "inspiration machine" comprising three independent rings, each featuring 180 labels, which suggest the degrees in a triangle that can be combined to form phrases. Each rotation produces one of 5,832,000 possible word combinations that act as a motif for a subsequent creative process. This "machine" can be interpreted as a "proof of concept" that even with a "banal"—and "monoaesthetic" (Schiesser 2004) medium such as words/phrases—acting as an initial starting point, it seems possible to create interesting and fruitful inspiration. This phenomenon gave us reassurance and certainty that our first prototype, despite its equally banal structure comprising purely basic shapes, such as triangles and rectangles as shadow casters, could nevertheless

[1] See also: https://www.russellawheeler.com/ruth-noller-creativity-formula

produce meaningful (i.e. inspirational) output.

2. “Schattenspiel”, (shadow play) by Hans-Peter Feldmann—an assortment of toy figures and bric-a-brac arranged on slowly revolving turntables. The light shining on the objects causes shadows to be cast onto walls. The shadows evoke wonderment, which encourages the audience to see simple everyday objects in a new light. We interpreted this piece as a “proof of concept”/confirmation that shadows contain an enormous bandwidth of transformational and inspirational qualities.
3. “Zoetrope”, “Daedalum” or “Wheel of the Devil” by British mathematician William George Horner (1786–1837). This machine is one of the first devices that could achieve animation through the rapid succession of otherwise static images (Horner 1834). The invention strongly influenced the basic configuration of our prototype—since the “Zoetrope” was not built to do any physical labour yet recalls the modus operandi of “real” machines—at least in its visual appearance.

Design and configuration

The integration of all key inspirations into a singular device serves to outline the fundamental form and function of our first prototype. Dubbed the “Landscape Wandering Machine”, this prototype was constructed as a rigged and animated 3D model comprising 48 objects arranged in fixed positions on three concentric rings that can be rotated independently. Six moving light sources were utilised to illuminate the scene, casting shadows onto a plain tableau at the centre. Initially, the prototype’s configuration was relatively basic, yet the resulting shadow images captured from the tableau were deemed promising for further exploration and experimentation due to the non-deterministic interplay of the shadow casters. However, it is important to note that these images, similar to the phrases in Tansey’s and Buener’s “Wheel”, are not the final product/outcome, but rather serve as an initial starting point for further transformations; thus, they are referred to as “maps” in subsequent discourse. In a sense, this prototype occupies a meta-state between abstraction and concretisation, as it was created and tested entirely within the digital space of CAD software, and initial experiments and probes were conducted exclusively in that realm. However, it also gave rise to the first haptic model, which was produced by 3D printing (Figure 1, right image).

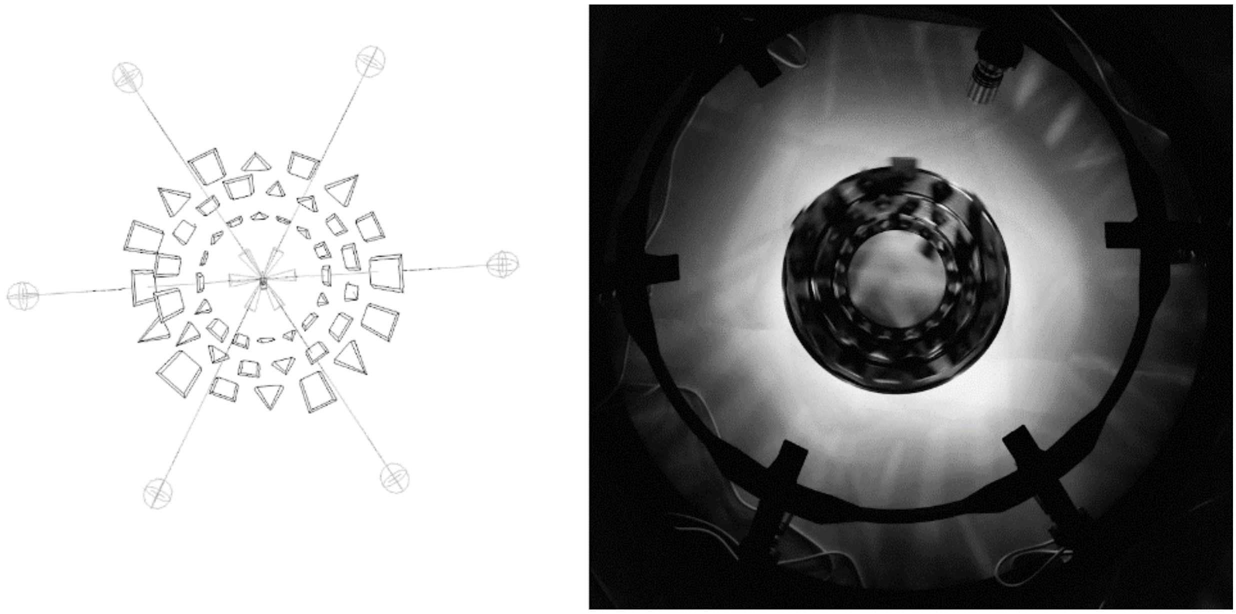


Figure 1: The digital prototype and 3d printed prototype with LED based light rig.

“Sketching” with probes

Using the initial concept of “obstinacy” (*Eigensinn*) described above, we started working on this prototype. We should mention here that we regard a prototype in this early conceptual stage of exploration, development and design as a conglomerate loosely assembled in a common media format. The aim of the prototype is to create a “gravitational centre” that tries to initially pull the disparate elements together as a compositional assembly, “bringing parts, materials, functions, structures, processes, activities, and events together in such a way that they have an emergent presence or an appearance in the world.” (Nelson and Stolterman, 2003). For our part, the role of the prototype, as described by Herbert, relates to designers’ sketches, “not of passive recording but of active participation in formulating the design” (Herbert 1993). The choice of using simple geometrical objects such as rectangles and triangles was in a direct and effortless way to transform the words and statements of “the Wheel” into a visual realm. This is because our intention was to work on a design that thrives and communicates back to us visually during the entire research and machine construction process. The physical prototype and later the *Knowledge Horizon Trajectory model* (KHT, see Fig. 2) became a vehicle for our tacit knowledge exchange from our former practices and experiences. “The tension here is between the knowing of the corporeal, so fluid and effortless, pushing against the need to verbalise through the cognitive” (Budge 2016).

At the beginning of the first iteration, we stayed true to the “traditional” concept of prototyping: by maintaining a 1:1 relationship between the digital and the real model, we created a “twin” with which we could simulate the state of the respective counterpart. Not least because of the physical distance between the two artists involved (Sweden–Germany), this aspect was essential. It was a deliberate design decision to articulate, as well as to blur the borders between digital and mechanical machines and interfaces. This created an almost contradictory interestingness and ambiguity that nurtured our individual imagination, since “in the art-based design research, the imagination is the intellectual medium that synthesises antitheses, turns difference into likeness, unifies oppositions and does so in pleasing and striking ways" (Murphy, 2017). To our surprise, the images that emerged in both prototypes were rather complex structures that were formed from overlapping shadows and were very different from the simple shapes of triangles and rectangles from which they were created. Here, the idea of using probes as a sketching technique emerged as a method for the design and exploration of the shadows that the prototype created.

In contrast to the experiment, which takes place in a controlled environment that aims to achieve replicability as well as objectivity and involves the experimenter having at least one hypothesis of the expected outcome, the aim of probing is to be feasible in a pluralistic environment and embrace ambiguity as a creative force. Thus, the probe does not aim to achieve any "epistemic validity", but instead strives to expose the *Eigensinn*, i.e. the inherent uniqueness of the symbiosis between the medium and the interacting subject. The designed and ready-made or crafted probes then became a process of knowledge acquisition or learning from the previously unknown within the areas of the conceptual and concrete space of the prototype. The knowledge acquired by the probes not only pertained to the particular domain of the machine, but also to the process of creating the machine and its component parts. Thus, we acquired knowledge by using probes on how to evolve the machine and how to construct and run it, based on what it can visually output. The probes helped us create a "richly textured but fragmented understanding of a setting or situation, to inspire what might be" (Boehner et al. 2012). This approach does not explicitly define and reduce the machine to a sole function but instead enables us to continually generate something visually, to develop hidden potentials to be discovered or rediscovered. By using probes and probing the prototype, we were able to create complex, associative and multi-layered maps (our chosen output) that could be visually captured on the intended surface on which in turn new families of association and structures of meaning were to be established. It pointed us in the direction of *Klecksography*, a creative method where inkblots are used to create stories or poems about the shapes formed by the ink. The uncertainty engendered by these ambiguous figures was very much in line with what we expected in this early stage. As recorded sketches, they "provide a flexible and dynamic external memory in which designers can place ideas for later inspection, and they also present visual cues that allow designers to associate functional issues with emerging structures" (Suwa and Tversky 1996; see also: Tovey et al. 2003). In retrospect, the physical and computational space of the shadows in our first prototype was a fairly straightforward process to construct, but for each probing activity, the level of complexity increased and paved the way for even more new considerations regarding the designed computation and the quality of the outcome—from methodological choices in the "machine's" design to parameterisation.

The Knowledge Horizon Trajectory model (KHT)

To be able to visualise and find a common ground in which we could identify and collectively reflect on our prototyping activities, we created a model of our pursued approach of prototyping. This was achieved by articulating a circular field, referencing the gravitational centre of the established knowledge (see also: Nelson and Stolterman (2003)) in which our compositional assembly was placed. For each probing activity, we then drew a line ("trajectory") from the model's centre to show whether the probing activity confirmed our prior knowledge—what we refer here as our knowledge horizon (KH)—whether it exceeded our assumptions, or whether it pointed us in the direction of "unknown unknowns" (e.g., there may be aspects that are currently unknown to us, and we may not even be aware that we lack knowledge of these areas.). In addition, the model facilitated our comprehension and articulation of constraints, limitations as well as possibilities and potentials that extend beyond the primary focus of the prototype, engendering discussions of potential issues and concepts related to scenarios that have yet to arise. Furthermore, the metaphor underlying the KHT can also be extended to further aspects. One such aspect to be discussed here is the function of “gravity”, i.e. the autonomous force which influences and distorts the “forcefield” established through the KH. In our model, the artist(s) could serve as such a force, attracting distributed aspects/objects that already exist within the KH through their sheer presence and, in particular, their personality (i.e., their “wilful obstinacy”/*Eigensinn*). By transformational manoeuvring, (re-)combining and (re-)composing these (heterogenic) aspects/objects, new constellations of epistemic objects can be created (i.e. new ideas emerge), which, in turn, possess the potential to expand the KH through their own gravity/inertia.

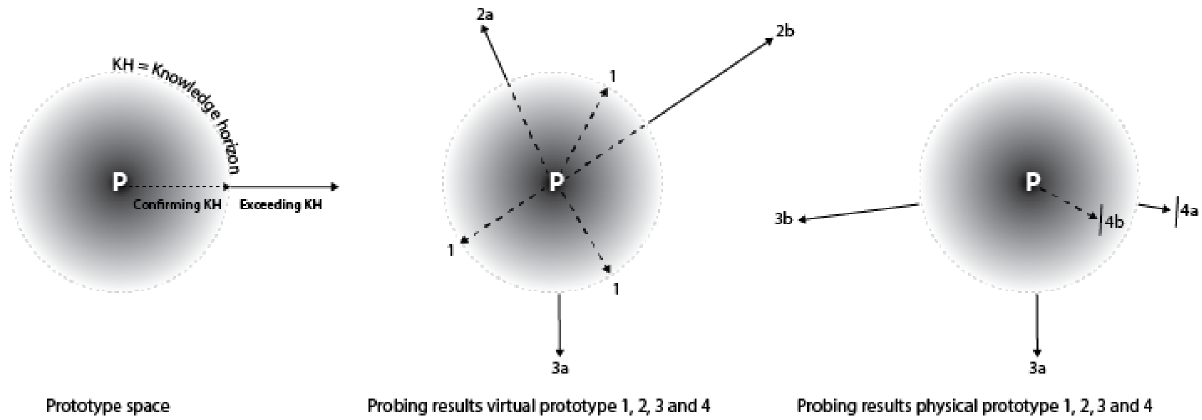


Figure 2: KHT model with examples of a probe’s possible trajectories within the creative space in relation to the “knowledge horizon”.

From abstractness to concreteness: Applied examples of the prototype’s epistemology

The following section aims to illustrate how we aggregated forward and noted the trajectories exhibited in the KHT model by showing some specific examples of the probing activities that we conducted with our prototype.

Probes used to explore, stress and play with specific known features inside of the knowledge horizon (trajectory 1 in our model)

HDRI. Given that the intensity and position of light naturally have a significant impact on the resulting shadow maps, even seemingly insignificant changes in the parameters of the light sources resulted in substantial variations. Our initial approach to this phenomenon was an attempt to “freeze” these parameters in order to establish reproducibility. Thus, the brightness values on the tableau’s surface were transferred into a static 360° high dynamic range image (HDRI). As this process is a standard procedure in computer graphics, it was determined that this method could also be successfully applied to our prototype. However, it was also noted that this significantly restricted the ambiguity and unpredictability of our machine which, while desirable in a “traditional” interpretation of a prototype, did not prove beneficial for our paradigm of interaction, which focuses on the inspirational qualities of the “machine”.

Virtual camera. The generation and rendering of the shadow images were carried out in the digital realm using a “virtual camera” that converted the shadow maps that had been created through ray tracing into image files. As this “camera” is designed to simulate a physical camera, it permits multiple parameters to be set, some of which had a significant impact on the shadow images. Specifically, we probed the combination of animation and motion blur/shutter speed, as well as the depth of field and digital noise through film simulation. Although these experiments yielded interesting results, they ultimately confirmed already-known information. In fact, they revealed yet another meta-level: due to the presence of these alienation effects (“*Verfremdungseffekt*”) in the shadow images, they contaminated the images of an ambivalent, unpredictable, virtual machine (our prototype) with artefacts of a calculable, functioning and ultimately simulating system (the render engine).However, the work on the camera’s parameters also highlighted how this plethora of settings required a different and more intuitive input method that is capable of consolidating multiple individual parameters into meaningful concepts, thereby enabling a creative form of “playing” with the prototype. This probing endeavour is presented in the next paragraph.

Rigged multimodal interaction. To be able to *exploit* the multitude of parameters and adjustments that are theoretically possible in the digital realm, we implemented a MIDI controller that was directly connected to our CAD software and that was able to manipulate and tweak six light sources simultaneously. Besides the more intuitive user interface, we also merged some individual parameters into groups that can be tweaked using one haptic knob/key. The results confirm the value of implementing a playful approach to interact with multiple parameters simultaneously, as it facilitates a rapid understanding of the shadow space and its unique characteristics for future parametrisation.

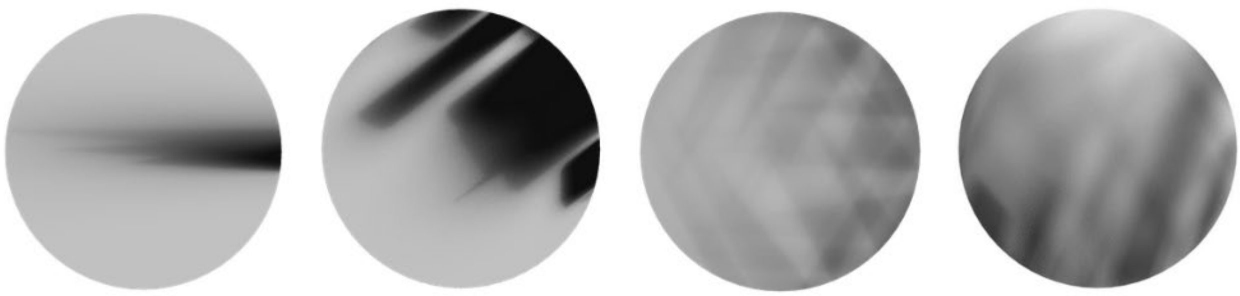


Figure 3: Exploiting, layering, staging, posing, and composing.

Probes used to explore, stress and play with a specific known feature that will eventually exceed/break the gravitational field of the prototype and therefore exceed the knowledge horizon

Probing with different image formats such as tif, tga and png (trajectory 2a): In our work on transformational stepping (see below), we noted that the dynamic range of 8-bit images was not sufficient to produce high-quality displacement maps. Thus, the OpenEXR file format with its 32-bit pixel depth will be our candidate in the next prototype. Since this format features a broad range of capabilities that require a corresponding workflow, we expect that a more in-depth understanding of its capabilities will be necessary—which can itself be developed through probing explorations.

Probing via a concept of transformational stepping using displacement maps (trajectory 2b): In the quest of “moulding” a “mountain”, we used the concept of recursion in a series of displacement map renderings. We tried to interfere with the machine by introducing different masks (2D as well as 3D) into the machine’s recursive rendering process to slowly steer it towards something that resembled the shape of a mountain. The results were beyond our expectations. The mountain-like landscape included several unforeseen properties and qualities and underlined that the prototyping processes, by using lights and rotating objects, could produce quite complex results.

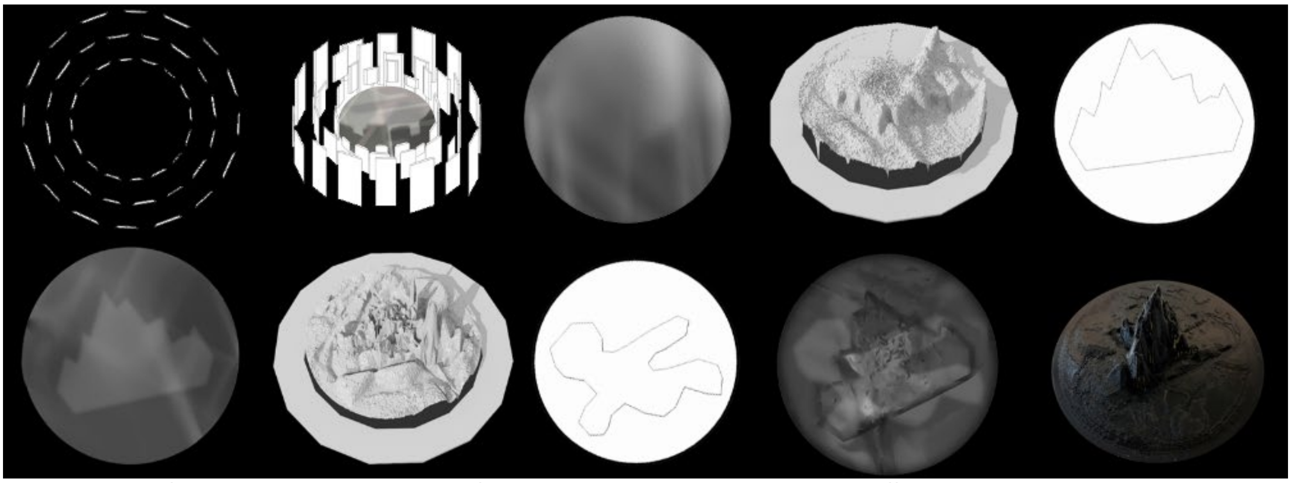


Figure 5: Transformational stepping. To interfere with the machine by introducing different masks into the machine’s recursive rendering process, leading from map to a 3d printed model.

Since the generation of the “mountains” relied on the recursive use of displacement maps, the quality of their rendering, as discussed in Section 2a, was found to be of exceptional significance. This process also challenged the rendering engines that were utilised, pushing them to their limits. By reusing and transforming 2D renderings—typically the final result of a design process—into 3D objects, a plethora of quirks and errors in the images were revealed, which would otherwise not have been apparent. It was noted that these subtle errors that were revealed through this transformational process (Boden 2003) possessed their own distinct and appealing aesthetic. Although the method of rendering in a CAD environment is well-established (i.e. confirming the KH), the “overdriving” of this process led to new insights. This trajectory takes the prototype from a stable to an unstable state, “at the edge of the knowledge horizon”, until a new stable condition is ultimately reached that exceeds the KH.

Unknown properties of the concept of the machines that were discovered in unknown parts (negative space) of the prototype and that can be introduced in the next iteration of the prototype

Trajectory 3a: The materiality of the disc became an issue and demonstrated how the material aspects of the disc itself in both virtual and physical models are significant and will be addressed in future prototypes. Should we deliberately play with different materials or lock it as a static parameter, focusing on other aspects of the machine’s components?

Trajectory 3b: Certain characteristics of the physical light sources we used were difficult to transfer to the digital domain. Specifically, the LED optics exhibited chromatic aberrations and diffractions that introduced highly “interesting” effects to the shadow images. We discovered that each lamp possessed its own unique qualities, which could also be tweaked by adjusting the optics. In principle, the digital prototype would be capable of reproducing these unique qualities, provided the individual characteristics of the lamps were known. However, it was the “haptic” and intuitive quality of the physical object that ultimately inspired us to consider further exploration in this direction.

Constraints and limitations

Trajectory 4a: Self-Illumination: As previously discussed in the chapter on virtuality and simulation, the goal of the physical and digital prototype was not to achieve complete equivalence of both domains (i.e. implementing a “digital twin”), but rather to facilitate and exploit the specific *Eigensinn* (“obstinacy”) of the respective medium. This allows for the opportunity to create material properties in the digital prototype that are difficult or impossible to replicate in the physical world, yet which still could impact the resulting shadow maps. For example, we probed emitting, semi-transparent and fully absorbing materials for the silhouettes. Since these properties of the material either demand specific measures or cannot be replicated at all with the physical prototype, we hit a hard boundary with this probe. Although they were initially frustrating, these constraints also nurture the creative process since they define and outline the “conceptual space” for each respective domain. It therefore becomes apparent why the prototype’s transformations and its general transformative qualities are of such importance to the creative process: By translating from the digital into the physical realm and vice versa, the specific *Eigensinn* of the opposite domain becomes apparent.

Trajectory 4b: An observation that we were able to make by utilising the haptic prototype was the specific characteristics of the light sources we employed. The attributes of said sources (such as beam angle, falloff, etc.) also defined the physical dimensions of the prototype. While in a digital environment, a light source can be infinitely small or infinitely distant, this is not possible in a physical space. Here, we encountered a hard boundary that constrained the replication of the properties of the digital prototype in the analogue realm.

Playful explorations towards a second prototype

Skopéin

While previous investigations yielded distinctly digital outcomes, on this occasion, a digital prototype was employed as an “instrument” to furnish input for a media art installation titled “Skopéin”. The installation was exhibited from late August to September 2022 at the *Stadtkirche* in Karlsruhe and explores the symbolic nature of the depiction of a “Heavenly Jerusalem” through an immersive 8m x 8m projection (Figure 6).

Figure 6: The Skopéin-Installation in the main church in Karlsruhe/Germany.

The artwork acknowledges the “atmosphere” of the venue by incorporating the colour scheme and the brutalist architecture of the church in its aesthetics. The projection, which comprises a 120-second animation, reduces the topos of a “Heavenly Jerusalem” to a pure abstract formal language. This animation was exclusively created in digital space by creating and animating an abstract and perpetually unfolding object, algorithmically. Through its reflective surface, the object depicts and distorts its surroundings which are visible in the multiple reflections, thus conferring the significant importance of these environments, although they can only be perceived “indirectly”. These environments were generated using our prototype by inverting the “mountains” produced in the “mountain probe” (see above), resulting in cave-like structures.

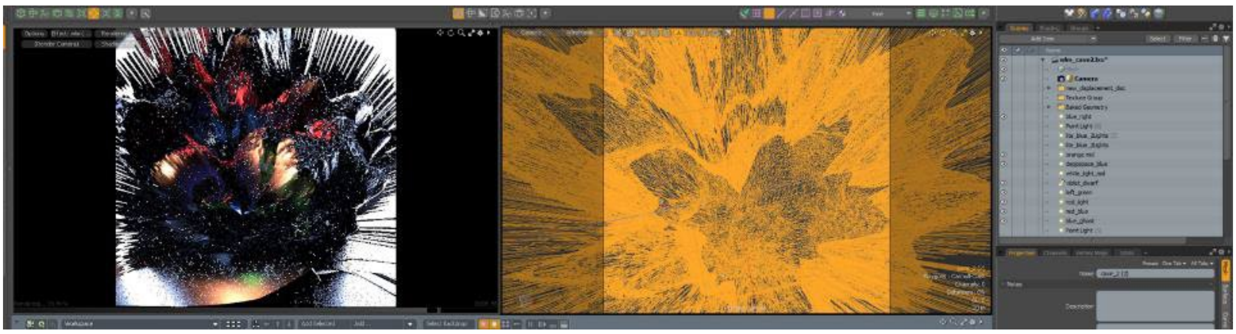


Figure 7: Maps transformed into 3d geometry illuminating it using various light sources as probes revealing and creating abstract spaces.

In these “caves” we manually placed lights as probes, both exploring the cave and illuminating it using various light sources, thus enabling the creation of highly abstract and “engaging” environments that fully met our aim of creating an abstract Jerusalem that might exist in the heavens.

Figure 8: Examples of illuminated “caves” produced by maps created by the machine.

The seemingly trivial transformational characteristics (grayscale image to 3D displacement) proved to be instrumental in providing valuable content by breaking the otherwise deterministic structure of a procedurally generated digital image by exploring features of the “cave” space with different light types to articulate its spatial qualities. Later we exploit each lightsource's respective properties in order to facilitate the appearance of “interesting” artefacts and errors while illuminating parts of the cave. In contrast to true randomness (which would have been an algorithmic alternative to breaking the deterministic nature), the “caves” still incorporated some degree of order. In retrospect, it can be stated that the success of this artwork can be traced to these particularities since they produced visual edge cases, in which the image oscillates between symmetry and chaos (Figure 8). As already outlined, creativity emerges in a “conceptual space” that embraces ambiguity and renders the expected finality to an affordance with no final conclusion. This phenomenon is not only relevant to the artist in the production process, but also to the audience of the artwork. Consequently, the artwork’s edge cases function as an affordance to facilitate the audience’s imagination. Thus, the “Heavenly Jerusalem” is synthesised in each contemplative act.

SoundScapes

The final transformation that we wish to expound upon in this discourse, which seamlessly aligns with the interaction paradigm we already conceptualised as “playing”, can be observed in our “SoundScapes probe”. This study utilised the physical prototype that features a video camera mounted above it that captures footage of the central tableau whereupon the shadow images are cast. Utilising the Processing programming language, the camera data is converted in real time into MIDI signals, which can then be transmitted to synthesisers or other MIDI-enabled instruments, such as samplers or drum machines. For this process, the individual colour channels of the camera's video feed were split and compressed to conform to the range of values that the MIDI protocol can accommodate.

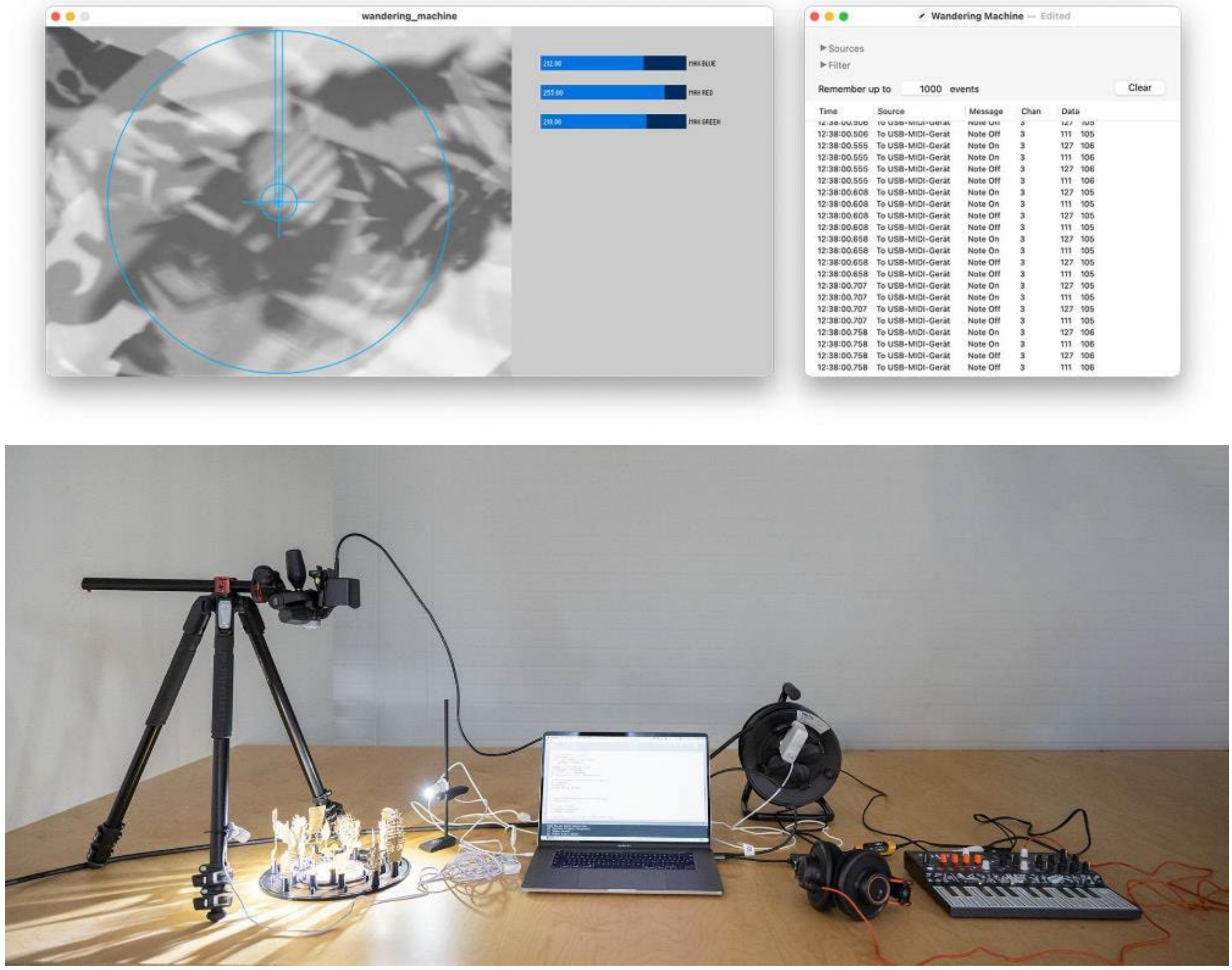


Figure 9: Screenshot of the Soundscape-project: the life camera feed (top left image) is converted into MIDI-commands (top right image) via Processing. Bottom image: The whole setup where the prototype is steering a synthesiser.

As illustrated in Figure 9, we also developed a rudimentary graphical user interface (GUI) to facilitate the alignment of the camera with the tableau and control the mapping of camera data to MIDI commands. While MIDI is capable of processing a wide range of control and notation data, we are currently only utilising a small subset of its capabilities, specifically, NoteOn, NoteOff, velocity, pitch and channel. Despite this limitation, our initial results have been promising as the setup allows us to play the machine like an instrument by altering the configuration of the silhouettes or the rotation of the concentric rings. In this manner, the shadow maps are transformed into a serial “score” that can be progressively read and interpreted. These promising results also provide the framework for contemplating a further experiment that utilises a digital prototype in lieu of a physical prototype. As already outlined, we have previously experimented with MIDI *input* devices which, in the context of the soundscape probe, can now be expanded to include the component of *output* if we use the digital prototype in a real-time rendering environment. In this manner, the prototype is transformed into a genuine virtual “instrument” that can be “played” but still incorporates the creative momentum that is created by the ambiguity and the unexpectedness of an inspirational device. Through this setup, whereby users interact with the instrument, they create a conceptual/virtual space—hence the name *SoundScape*—which corresponds with the creative space that is contoured by our model of the KHT. Therefore, the instrument both *is* and *creates* spaces, which users can decide to *explore* and *exploit*.

Preparing Iteration 2 of the machine

Even though the initial prototype produced intricate shadow images using basic shapes, we aimed to incorporate more detailed silhouettes in the subsequent prototype. Inspired by Peter Greenaway's project "100 objects that represent the world" (Greenaway, 1992), and his method of using symbolic items to communicate the life on earth, we set out to apply this method under the paradigms of our prototype: On the one hand, we are thereby *exploiting* Greenaway's project structure, and on the other hand, we are setting the stage for our own *exploration*, which seeks to determine which objects should be employed in the second iteration of the machine.. We ended up with a collection of 31 silhouettes in three different scales and appearances that possess a high degree of visual appeal (i.e. "interestingness"), in three distinct dimensions to address trajectory 1 in our model (Fig. 10). This was done in order to further "probe" with parameters and further exploit layering, positioning, posing, and composing within the new shadow space on the surface.

Figure 10: The new set of silhouettes developed for the next prototype.

In addition to our experimentation with the virtual light properties, we also conducted tests with their physical counterparts to investigate the disparities between the two, despite their comparable scale. As depicted in Figure 11, we utilized a constructed light rig featuring three distinct silhouettes to playfully explore and quantify the angles, intensity, and distance of the physical LED-based lights to acquire a more thorough understanding of where to place the lights and at what angle. This was done in order to identify the optimal positioning of the lights and silhouettes to interact and generate shadows on our circular surface. As a result of this pre-prototype activity, we made several modifications to our design. Specifically, we transitioned from flat to elevated rings to enhance the distribution of the silhouettes' shadows across the three rings, altered the overall composition density by reducing the number of silhouettes from 48 to 31, and employed prime numbers (7, 11, and 13) as fixed positions of the shadow casters on the concentric rings to minimize overlap.

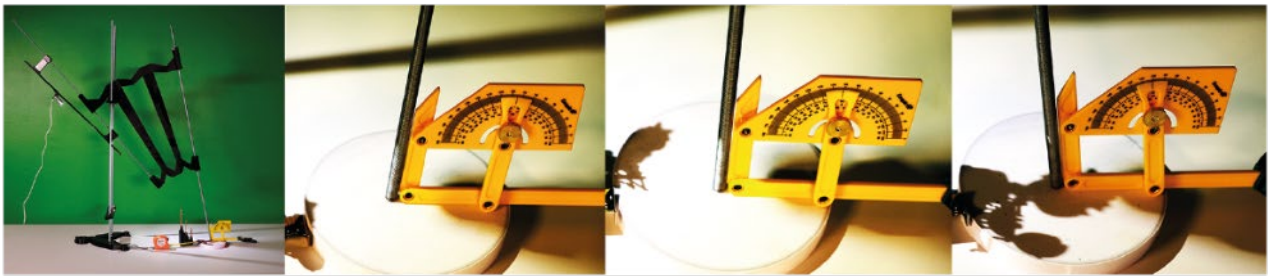


Figure 11: 3D printed light rig for playful and direct interaction with the light source, to rapidly understand which angles and distances of the lighting are most favourable.

Conclusion

Through the work and experiences described in this paper, we would like to emphasise that increased complexity in creative development still calls for both disciplinary depth and integrative skills when working with prototypes. Thus, there is a demand for a deeper challenge between virtual and physical objects, and a desire to explore their incompatibilities, rather than merging them together into one. When we engage in such activities and have ideas and concepts that emerge out of vague situations, prototyping using different media and materials plays an important role in conceptualising the known and unknown. We can never initially know whether the compositional assembly is appropriate or suitable, or if the chosen or created components are insufficient. Here, we would like to address the importance of imagination, bridging us from the proverbial *what-is* to the *what-if* (Hopkins 2019). The model we initially used soon began without any intention from our side to function as a notation system, a cumulative way to mark our findings in the KHT model while designing, tweaking, and testing the prototype and the parts as we progressed. This helped us to document our findings and shortcomings, inside of the knowledge horizon within the model. Using the trajectories to direct us to new areas of unexplored terrain, provides us with what might also be used in the next prototype iteration. Finally, in relation to our work on the prototype model, we would like to emphasise that in prototyping activities, it is important to know when to *explore* new ground by directing your attention elsewhere, and when to *exploit* and look more deeply at the material you have at hand.

References

Boden, M. A. (2003). The creative mind: myths and mechanisms*. Routledge, London.*

Boehner, K.; Gaver, W.; Boucher, A. (2012). Probes. In: Lury, C.; Wakeford, N. (Eds.) Inventive Methods. The Happening of the Social. Routledge, London: 185–201.

Budge, K. (2016). Teaching art and design: Communicating creative practice through embodied and tacit knowledge. Arts and Humanities in Higher Education, 15(3–4), 432–445. https://doi.org/10.1177/1474022215592247

Folkmann, Mads Nygaard (2014). Unknown Positions of Imagination in Design. Design Issues, 30(4), 6–19. http://www.jstor.org/stable/24266978

Greenaway, P. (1992). Akademie der Bildenden Künste in Wien, eds., Hundert Objekte zeigen die Welt: 100 = Hundred objects to represent the world. Verlag Hatje, Stuttgart.

Herbert, D. (1993). Architectural Study Drawings. Van Nostrand Reinhold, New York.

Hopkins, R. (2019). From What Is to What If: Unleashing the Power of Imagination to Create the Future We Want. Chelsea Green Publishing, Chelsea.

Horner, W. G. (1834). On the properties of the Daedaleum, a new Instrument of Optical Illusion. In Brewster, D.; Taylor, R.; and Phillips, R., eds., The London and Edinburgh Philosophical Magazine and Journal of Science. London: Taylor and Francis. 36–41.

Hui, Yuk (2019). Recursivity and contingency. *Rowman & Littlefield International, Washington, DC.*

Isaksen, S. G.; Dorval, K. B.; Treffinger, D. J. (2011). Creative approaches to problem solving: A framework for innovation and change. SAGE, Los Angeles and London.

Lévy, P. (1998). Becoming Virtual. Reality in the Digital Age. *Plenum Trade, New York.*

Murphy, P. (2017). Design Research: Aesthetic Epistemology and Explanatory Knowledge. She Ji: The Journal of Design, Economics, and Innovation,3(2), 117-132.

Nelson, H. G.; Stolterman, E. (2003). The Design Way. Intentional Change in an Unpredictable World. *MIT Press, Cambridge, MA.*

Olsson, G. (2007). Abysmal: a critique of cartographic reason. *University of Chicago Press, Chicago.*

Ryan, M. (2015). Narrative as Virtual Reality 2. *Johns Hopkins University Press, Baltimore.*

Schiesser, G. (2004). Arbeit am und mit EigenSinn. Medien | Kunst | Ausbildung, oder: Über den Eigensinn als künstlerische Produktivkraft. In: Schwarz, Hans-Peter (Ed.). Produktionsweisen. Zürcher Jahrbuch der Künste. Vol. 1. Hochschule für Gestaltung und Kunst, Zürich, 174–193.

Siess, A.; Hepperle, D.; Wölfel, M.; Johansson, M. (2019). Worldmaking—Designing for Audience Participation, Immersion and Interaction in Virtual and Real Spaces. In: Brooks, A., Brooks, E., Sylla, C. (Eds.) Interactivity, Game Creation, Design, Learning, and Innovation. ArtsIT DLI 2018. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol 265. Springer, Cham, 58–68.

Suwa, M., & Tversky, B. (1996). What architects see in their design sketches: Implications for design tools. Human factors in computing systems. In CHI'96 conference companion. New York: ACM, 191–192.

Taylor, M.; Tansey M. (1999). The picture in question: Mark Tansey and the ends of representation. *University of Chicago Press, Chicago.*

Tovey, M. J., Porter, S., & Newman, R. (2003): Sketching, concept development and automotive design. Design Studies, 24(2), 135–153.

Michael Johansson
Artist, Associate professor in Design, Researcher at the D.A.R.C Kristianstad University Sweden. https://www.hkr.se/om-hkr/organisation/fakulteten-for-ekonomi/medarbetare-fakulteten-for-ekonomi/michael-johansson/ Born 1962, Gothenburg, Sweden. Educated at the royal college of fine arts in Copenhagen 1984 -1990. Through the years I have been involved in research at the Interactive Institute, Space and virtuality studio, and worked at Malmo University arts and communication. From 2010 I work at the Department of Design at Kristianstad University, Sweden. I do research in human and computational imagination and how it it used in planning, design and the arts. Represented in Moderna Museet (museum of modern art) Stockholm and Malmö art Museum collections.

Andreas Siess
Andreas currently investigates forms, formats and aesthetics of science communication in the arts and humanities for the Rhine-Ruhr-Center for Science Communication Research at Hochschule Bonn-Rhein-Sieg university of applied sciences in Germany. As a designer with a strong focus on research he is interested in developing new ideas for implementing creative techniques in the academic education. In his PhD-project he investigated the aesthetics of virtual environments and argued that our visual understanding as well as our semantic language of VR was formed in the early 1800s. Furthermore he experiments with immersive and interactive media art and exhibited in international contexts, such as: Venice Biennale Architettura, ZKM Karlsruhe and much more.

Bee Buzz Buddy: An Interactive Digital Toy to Facilitate Tangible Embedded and Embodied Interactions for Young Children's Active Play

Yuehao Wang, Queensland University of Technology, Australia
James Dwyer, Queensland University of Technology, Australia
Nicole E.M. Vickery, Queensland University of Technology, Australia
Bernd Ploderer, Queensland University of Technology, Australia
Dannielle Tarlinton, Queensland University of Technology, Australia
Alethea Blackler, Queensland University of Technology, Australia

Abstract

Tangible, Embedded, and Embodied Interactions (TEIs) can support children's physical activity through play, by leveraging technology and children's bodily movements. However, many existing TEIs have been focused on older children, and they offer limited interactions that are not comparable to physical activity. In this paper, we report on our investigations of the design of TEIs to inspire new forms of active play, to create opportunities for preschool children to engage in physical activity. We designed the Bee Buzz Buddy, a digital toy that provides multiple forms of digital prompts and direct feedback to children's bodily inputs to invite active play through games. These games involve aspects of pretence, role play, and imaginative play. This paper describes the process conducted to arrive at the concept of the Bee Buzz Buddy, then presents the design details and the interaction scenarios. We conclude by presenting the next steps, including iteratively evaluating aspects of interaction to improve the design.

Active Play; Children; Digital Toys; Interaction Design; Tangible Embedded and Embodied Interactions

Many children aged 3 to 5 years old do not participate in adequate physical activity (McNeill et al, 2020). This is problematic because physical activity is important to children's well-being, motor skills development, and school readiness (Duncombe, 2019). Children tend to participate in physical activity through play, particularly active play (Brockman et al., 2011). Through active play, children can expend energy in a freely-chosen, fun, and motivating manner (Truelove et al., 2017). However, young children's opportunities for active play may be restricted. At home, the most significant barrier that children experience to their daily active play is limited space - e.g., apartments lacking adequate space (Hesketh et al., 2017). In outdoor playgrounds, challenges include a lack of play equipment or play facilitators, the impact of weather, potential safety risks, and the fact that young children rely on their parents for transportation and supervision. Additionally, Tandon et al. (2015) identified that children's activities in childcare centres were 73% sedentary. Consequently, for many young children, their active play is limited by external factors. Therefore, young children should be provided with appropriate materials to support them in active play, which will create opportunities for them to be physically active.

Building upon our extant work, in this paper we present the design of Bee Buzz Buddy prototype, a digital interactive toy designed for encouraging young children's active play by facilitating Tangible, Embedded, and Embodied Interactions (TEIs). The prototype can provide children with a wide range of activities, where children can exert themselves and practice their Fundamental Movement Skills (FMS) (i.e., locomotor, body management, and object control skills) through games. These games involve aspects of pretence, imitation, role play, and imaginative play. These aspects are not only beneficial for children's physical but also social and cognitive development (Lynch et al., 2017). In this paper, we start with an overview of related work and describe the design process for this prototype, including the methodology and the research conducted to arrive at the final concept. We conclude by describing the limitations and the next steps.

Related Work

Children's Play

Play is essential to preschool children's development. Through play, children refine their physical abilities such as coordination and muscle strength (Cammisa et al., 2011), and they also develop their self-concept and creativity (Pellis & Pellis, 2007). Play is diverse, as illustrated by the varied types of play (Sutton-Smith, 1997). In this paper, we focus on active play and imaginative play. Active play involves children in games and playful activities, making them "huff and puff" (ACT Government, 2020). Imaginative play allows children to immerse themselves in an imaginary scenario and act out pretend roles (Sawyer & Brooks, 2021). It is predominant in preschool children's play activities as they develop their intellectual and communication abilities (Howard, 2013). Therefore, we believe that blending imaginative play with active play offers an approach to address young children's physical inactivity, which can also be beneficial for their creativity and communication development.

Active Play

Active play is a child's version of physical activity (Truelove et al., 2017). We have drawn together the perspectives of education (Pellegrini & Smith, 1998; Swift, 2017), early childhood development (Pakarinen et al., 2020), and health (Brockman et al., 2011; Truelove et al., 2017) to define active play as *a combination of fine and gross motor activities that impacts early childhood development, in which children exert energy in a freely chosen, fun, and motivating manner. Active play can involve various of contexts including indoors or outdoors, structured or unstructured, solitary or social, and gamified activities* (Tarlinton et al., 2022). We understand that active play is quite broad, encompassing a wide range of activities and contexts.

Through active play, children can practise their Fundamental Movement Skills (FMS), which they need to be proficient at in order to take part in complex games and learning as they grow (Swift, 2017). Activities that target different FMS may require different toys or equipment. Locomotor activities are where children transport their bodies from one place to another (Goodway, 2021), such as running and jumping. Therefore, it is common for children to participate in such activities without any toys or play equipment. It is different for object control activities, as they require children to control objects such as balls, hoops, and ribbons (Wick et al., 2017). Lastly, body management activities are where children balance their bodies in stillness and in motion (Goodway, 2021), such as rolling and climbing. Children can engage in such activities with or without objects. For example, dancing is a type of body management activity that does not require any objects, while climbing requires objects (e.g., playground equipment) for children to climb on.

Imaginative Play

The terms symbolic, imaginative, and pretend play have been used interchangeably in the literature. In this paper we use the term imaginative play. It is unique from other forms of play in that it includes imaginative elements, where children impose imagination or 'pretend' on reality (Weisberg, 2015). Often imaginative play allows children to act out imaginary scenarios, role-play (e.g., playing mummies and daddies), and explore cultural elements (e.g., media). Imaginative play is often the most evident through children pretending that one object is another (Lillard, 1993). Engaging in imaginative play is important for young children's social and emotional development (Rao & Gibson, 2021).

Imaginative play can also provide motivations for children to be physically active by containing a role and a pretend situation in play (El'Konin, 1999). The connection between physically active play and imaginative play is evident in the literature. For example, in a study of children's preferences for active play, Harris (2018) identified a connection between children's outdoor active play and imaginative play, where children largely described imaginative elements in connection to physically active play, such as pretending to be animals, or imagining that they are in a jungle. Additionally, during the COVID-19 pandemic, U'wais et al (2021) found that imaginative play was a motivating factor for engaging in active play, such as engaging in imaginative play relating to TV characters or pretending to travel (an activity that was restricted during the pandemic).

Tangible, Embedded, and Embodied Interactions for Active Play

Tangible, Embedded, and Embodied Interactions (TEIs) present new opportunities for young children's active play. TEIs' characteristics of tangibility, spatiality, embodiment, and embeddedness enable them to encompass a wide scope of systems (Hornecker & Burr, 2006). These systems allow people to physically interact with computational objects in the real world (Frauenberger, 2020). As opposed to traditional interactions that utilise graphical user interfaces, these systems are more intuitive for children (Desai et al., 2019). This is because young children have minimal or developing literacy skills, while such systems utilise children's senses (i.e., hearing, touching, and sight) to communicate.

Materiality empowers TEIs to stimulate children's senses (Hornecker, 2011). Physical materiality refers to the tangible features (e.g., size, shape, colour) of TEI systems (Ardevol et al., 2016), serving as the representation and control of digital information (Cardoso & Ribeiro, 2021). Physical materiality provides clues for people to discover the actions they could perform with physical objects (Gibson, 2014), while digital materiality represents the intangible features of TEI systems (Ardevol et al., 2016). Intangible features are the digital outputs from the systems, which can act as prompts to initiate an activity, as attractions to stimulate children's interests, and as feedback to respond to children's actions (Wang et al., 2022). Through digital outputs, children understand the meanings of their actions (Leonardi, 2010). Therefore, effective interactions with TEI systems require careful configurations of materiality, both digital and physical.

Materiality has been widely embedded in the practice of TEI systems design. 'Gum' as an example, is an interactive toy that encourages children to take care of it through participating in physical activity to make it healthier and happier (Leal Penados et al., 2010). Its physical materiality, the soft material, conveys information that it is a cuddly toy. Also, its portable size informs children that it could be carried around. On the other hand, the digital materiality helps children to understand their actions. For example, acting as prompts, the 'Gum' can talk and emit sounds to express its mood so that children know how much physical activity they need to take part in. Further, acting as feedback, it can light up in its body and vibrate to communicate.

The design and implementation of materiality significantly affect children's interactions with TEI systems (Seo et al., 2015). Physical materiality plays a dominant role in attracting children to engage in active play activities (Wang et al., 2022). For example, a TEI system in a larger size (e.g., a playmat) or in a particular shape (e.g., a ride-on toy) can commonly encourage active play because it can physically afford children's whole-body movements. In comparison, some TEI systems also rely on digital materiality to invite active play. Our previous explorations identified that commonly observed digital features can be auditory (e.g., verbal instructions), visual (e.g., LED lights), and tactile (e.g., vibrations) (Vickery et al., 2021; Wang et al., 2022). These digital features become an important tool for communication between children and the system.

Recognising the important roles of materiality, we have identified gaps with existing TEI systems. First, few TEI designs were targeting 3- to 5-year-old children (Wang et al., 2022). However, young children are at an important developmental stage, and they develop dramatically as they grow (Canning, 2020). Systems designed for older children can be over-complicated for 3-to-5-year-olds to use. Second, many TEI systems failed to provide digital responses directly to children's bodily movements (Vickery et al., 2021). Yet, it is vital for a TEI system to provide direct and specific feedback to children's physical movements to successfully initiate and maintain their engagement in active play. Therefore, we see the opportunities to design TEIs specifically for young children, to encourage age-appropriate physical activities without restricting their imagination, novelty, and free play.

Design Process

Our design process has been realised primarily through a Research through Design (RtD) approach, accompanied by a series of methods including design space exploration, design thinking and user consultation. RtD has been shown to be useful in tackling problems that have not been solved in other ways (Blackler et al., 2018). Considering our project is aiming to help young children to become physically more active with the mediation of digital technologies, the RtD approach allows us to identify current problems with existing systems, iteratively ideate solutions, and empirically test determined solutions to evaluate their effectiveness.

The first stage of our design process included developing a rich understanding of the space. We adopted the design space exploration method, which allowed us to understand young children's current experiences with active play in their daily life. We conducted empirical research to gain this understanding. Herein, we conducted a scoping review of relevant literature as presented in Vickery et al. (2021), analysis of commercialised products as reported in Vickery et al. (2022) and Wang et al. (2022), and semi-structured interviews with parents and early childhood teachers as discussed in Tarlinton et al. (2022). From these explorations, we aimed to understand the barriers to, and facilitators of, preschool children's participation in active play. Table 1 summarises the established design objectives to address the identified gaps from our explorations.

Table 1 Correspondences of Findings and Objectives

Design Objective	**Identified Gap**
Transform sedentary screen time to active play by disregarding any forms of screens	Screen-based technology (e.g., iPad) was the most common digital equipment children use (Tarlinton et al., 2022).
	Screen-based technology was prevalent in the literature around TEIs (Vickery et al., 2021).
Design age-appropriate activities that adapt to children's developmental changes as they grow	Many commercialised TEIs targeted broader age groups (Wang et al., 2022).
	Literature around TEIs was for older children (particularly 5-9-year-olds) (Vickery et al., 2021).
Exploit children's interests in locomotor activities to practise their FMS	Locomotor activities were most commonly engaged in (Tarlinton et al., 2022).
Stimulate children's interest and imagination by encouraging imaginative play and inviting games	Children often incorporated sociodramatic play and made-up games into their active play (Tarlinton et al., 2022).

Led by these objectives and the results of our design space exploration, the research team took part in a design sprint, as a part of a design thinking process (Cross, 2006). During this sprint, we ideated a series of ideas to address the gaps identified in Table 1 (see Figure 1).

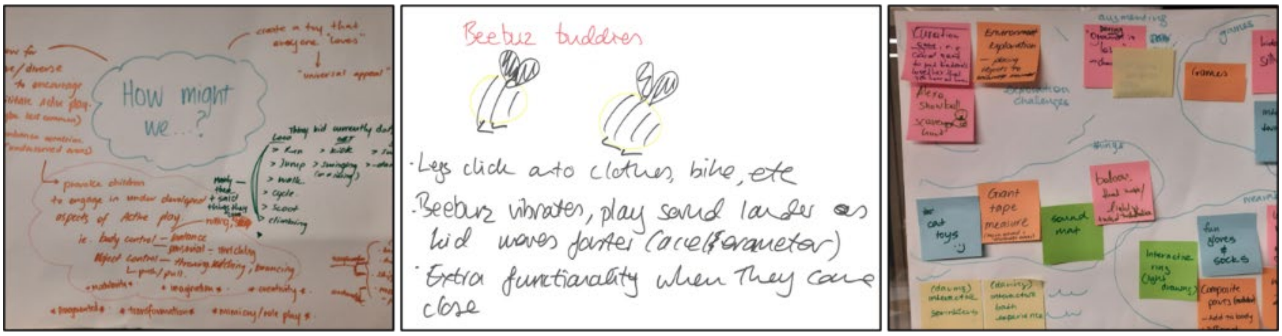


Figure 1: Examples of the Concepts Produced During the Team Design Sprints

The ideas developed from this session were further ideated and grouped together based on three conditions: 1) the physical existences (i.e., wearables, objects and toys, spaces, and playgrounds); 2) the featured themes (i.e., buddies, music and dance, film); and 3) the types of interactions (i.e., social, individual). Figure 2 shows the nine groups identified.

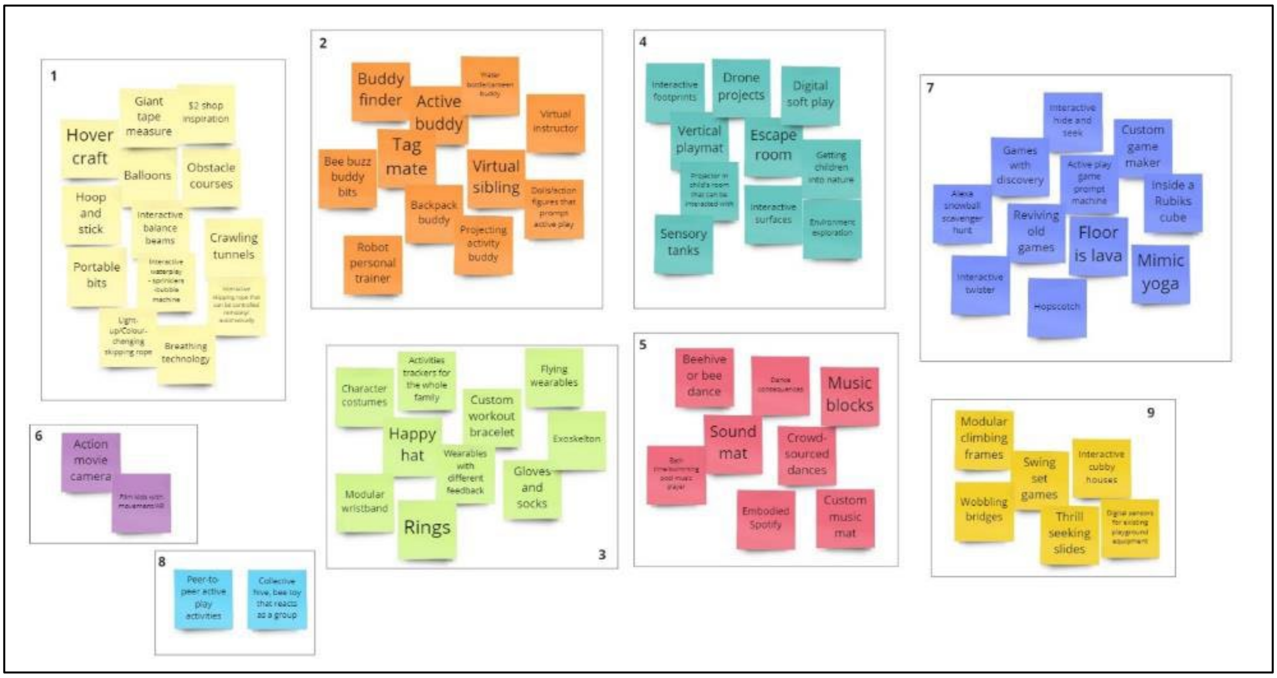


Figure 2: Design Ideas Categorised into Groups: (1) Objects and Toys, (2) Buddies, (3) Wearables, (4) Spaces, (5) Music and Dance, (6) Film, (7) Games, (8) Social, and (9) Playgrounds.

We then evaluated and selected ideas from these categories. This was achieved based on the criteria developed from stakeholders' needs as well as feasibility of development. Stakeholders include children (i.e., the child themselves and their friends/siblings/peers), and adults (i.e., parents, caregivers, and early childhood teachers). We combined the insights from observations, interviews, and scoping reviews conducted in our design space exploration as well as from the literature to develop a series of selection criteria, as listed in Table 2.

Table 2 Criteria Developed Based on Stakeholders' Needs to Assess Design Ideas

Criteria	Description
Flexibility	The designed activities should not be limited by space, meaning that children can participate in the activities in both indoor and outdoor play environments.
	The activities should allow for individual play so that they would not be restricted by the number of players.
	The prototype should be usable with other playthings (e.g., bikes, scooters) to uncover more interaction scenarios.
Novelty	The designed TEI should invite active play through games. Games can attract children's attention by stimulating their curiosity and providing challenges to act as a motivation factor (Yanez-Gomez et al., 2019).
	The designed TEI should also allow for role play and imaginative play, pretence, and imitation, to stimulate children's interests in imaginative play and made-up games.
Physical Features	The prototype should be portable and lightweight to be conveniently carried around and used in multiple contexts.
	The appearance of the design should provide inspiration for children's imitation, role play, and imaginative play.
Digital Features	Digital outputs should play a vital role in children's interactions with the TEIs to enhance their play experience (Wang et al., 2022). At the point of interaction, digital features should attract children's interest. To initiate an activity, digital features should provide affordances to encourage children's embodied movements. During the interactions, digital features should provide direct feedback to children's physical movements.

Based on the criteria, we selected seven ideas including collective hive (bee toy that reacts as a group), bee buzz buddy bits, backpack buddy, interactive hide and seek, beehive or bee dance, games with discovery, and wearables with different feedback. The Bee Buzz Buddy presented in this paper is an integration of these ideas. By employing a bee metaphor, it engages the child in pretend play to stay active. It is designed to stimulate children's sense of novelty by allowing for imaginative play. The prototype is also designed to be portable so that it can be used in various contexts that allow for flexibility. The design includes multiple games, not only allowing for discovery but also adding another dimension of fun to traditional games (e. g., hide and seek). The Bee Buzz Buddy features music and songs along with other forms of digital features including vibrations and light effects, where children's experience can be further enhanced.

Bee Buzz Buddy

The Bee Buzz Buddy prototype presented in this paper is developed as part of a larger project, exploring how TEIs can be designed to offer new opportunities to promote sustained engagement in preschool children's active play and support their development. The project aims to establish a framework to guide the future design of technology-augmented experiences for active play. The prototype is a mediator for us to gather information about children's active play experiences with TEIs and build our framework. The prototype is not an end in itself.

Prototype Design

The final design of the prototype consists of an interactive bee toy that children can carry around. The design is illustrated in Figure 3. It is designed with four games that target different FMS, including *Animal Jumps*, *Hide and Seek*, *Run to the Beat*, and *Explore*. The design does not require any abstract input tools such as the traditional joysticks or controllers for game play. Instead, the entire state of game play is embodied within the Bee Buzz Buddy, where all the interactions occur through the soft bee toy.

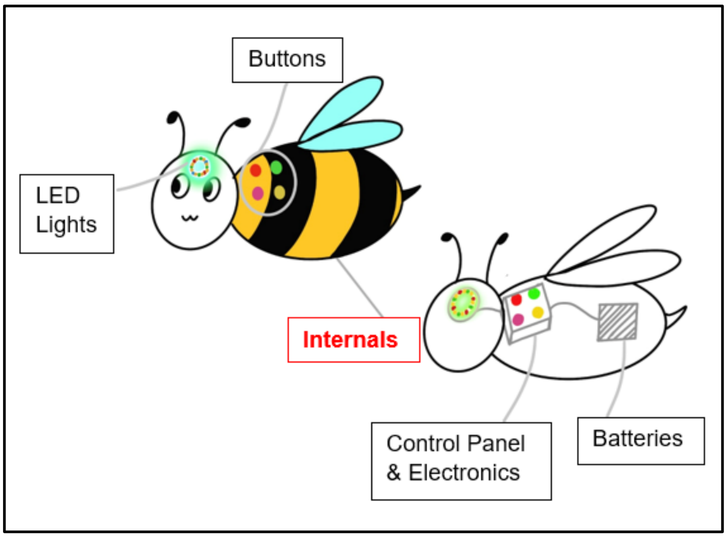


Figure 3: Overview of the Bee Buzz Buddy Design

The prototype uses an Arduino microcontroller to track user movement and facilitate tangible activities with children. Figure 4 is an overview of the components we used to develop the prototype. The Bee Buzz Buddy features a simple push-button interface for basic functionality such as activity selection and an Inertial Measurement Unit (IMU) sensor to detect specific types of movement required from the user during the activities. These inputs are processed by the microcontroller to trigger feedback from a haptic motor module, an LED ring module, and an MP3 module with a speaker. These modules are used to provide tactile and auditory feedback to encourage play and enhance the user experience. The device also incorporates a real-time clock and a data logger to track usage data so the researchers can understand when and how the participants are using the prototype.

The electronic componentry is then mounted into a soft bee toy using two electronic housings. The primary housing contains the microcontroller, battery pack, real-time clock, data logger, and MP3 module with the speaker. The secondary housing contains the input buttons, LED ring, and haptic motor modules. The two housings are both mounted within the main body of the toy. The primary housing is placed to the centre of the main body beyond children's reach, whereas the secondary housing is close to the surface of the toy so that children can press the buttons and receive the feedback.

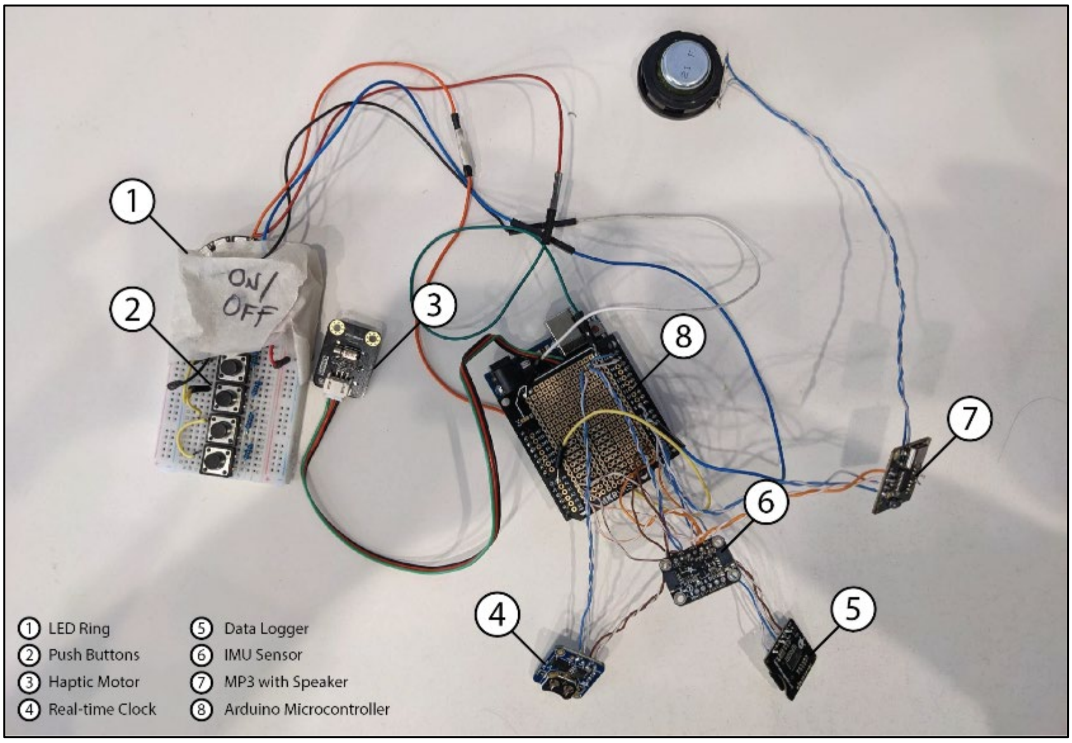


Figure 4: Hardware Components and Wiring of the Prototype

Children's Bee Buzz Buddy Activities

The Bee Buzz Buddy can be switched on with a simple button push, and it indicates it is on with rainbow LED lights. The child is then verbally prompted to select a game to play (see Figure 5).

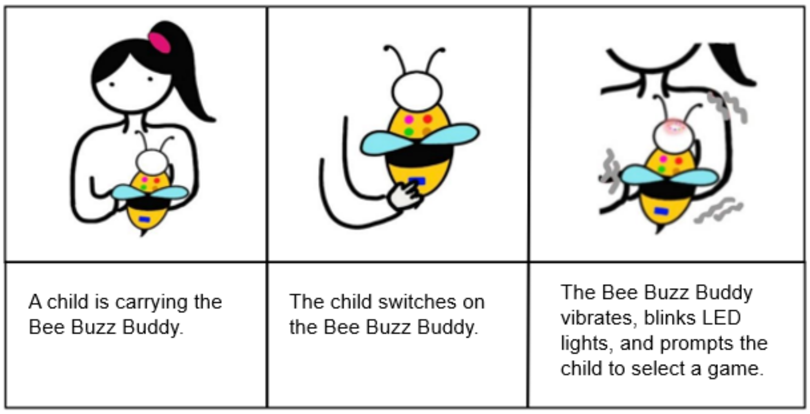


Figure 5: Storyboard Shows the Beginning of Interaction

Game 1 Animal Jumps

This game specifically encourages jumping and stomping that relate to children's locomotor skills. To participate in Animal Jumps, the child is asked to mimic the jumping behaviours of an animal. When the device registers that the child has performed a jump, the Bee Buzz Buddy plays a jumping sound effect, vibrates, and lights up to provide direct feedback to the child's bodily movement inputs. In this game, the Neo Pixel LED ring acts as a "loading bar", where the lights build up as the child jumps (see Figure 6). Figure 7 shows the interaction scenario of Animal Jumps.

Figure 6: LED Lights Respond to Movement Intensity

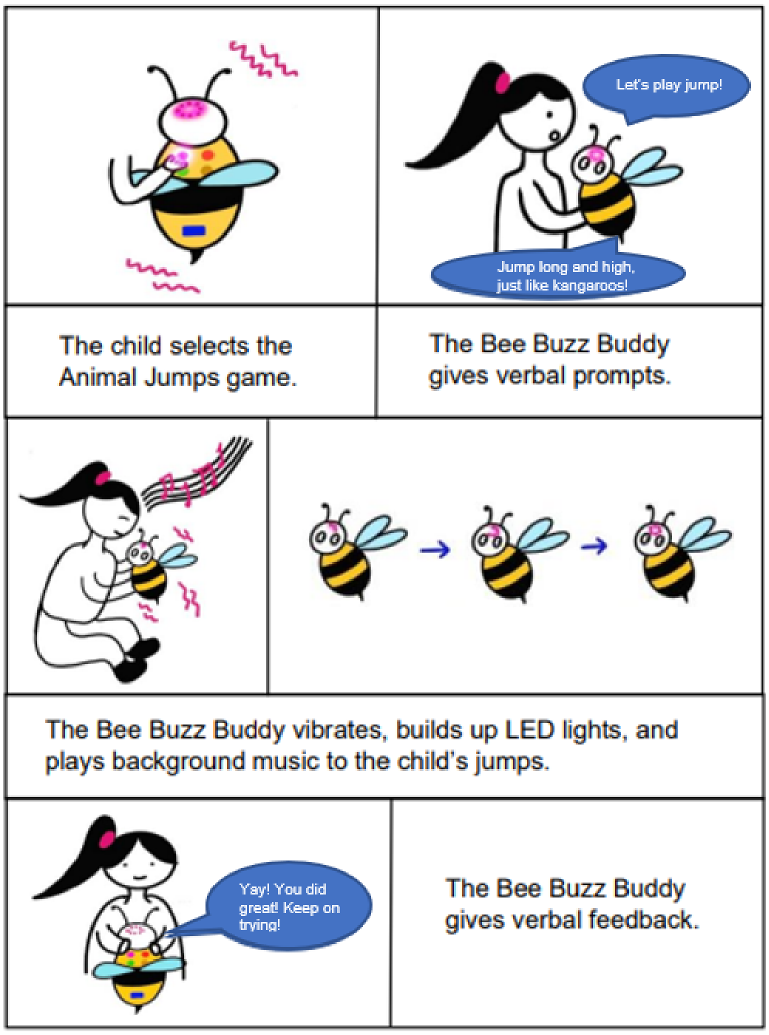


Figure 7: Storyboard of Animal Jumps Interaction Scenario

To register the "jump event", the toy uses an accelerometer which is a type of IMU sensor. When the child performs a jump, the toy tracks the change in acceleration within the vertical axis. When this change in acceleration exceeds the set threshold value, the sound, vibration, and light outputs are triggered. A simple debounce function was used to filter out any extraneous events and ensure the output functions were only executed once for each jump.

Game 2 Hide and Seek

In the Hide and Seek game, a second person hides the Bee Buzz Buddy toy while the child tries to find it. The toy also has a countdown timer displayed on the Neo Pixel LED ring, which shows the person hiding the toy how much time they have left to hide it. Once the timer runs out, the toy is 'armed' and ready to detect movement. If the toy registers movement that exceeds a certain threshold, it determines that the child has found the toy and picked it up. To do this, the toy uses all nine degrees of freedom (DOF) provided by its IMU sensor to track changes in its location and orientation. During the game a secondary timer also runs to determine the game's duration, and once a set threshold has been exceeded the toy provides audio clues to assist the child in finding it. Figure 8 shows the interaction scenario of the Hide and Seek game.

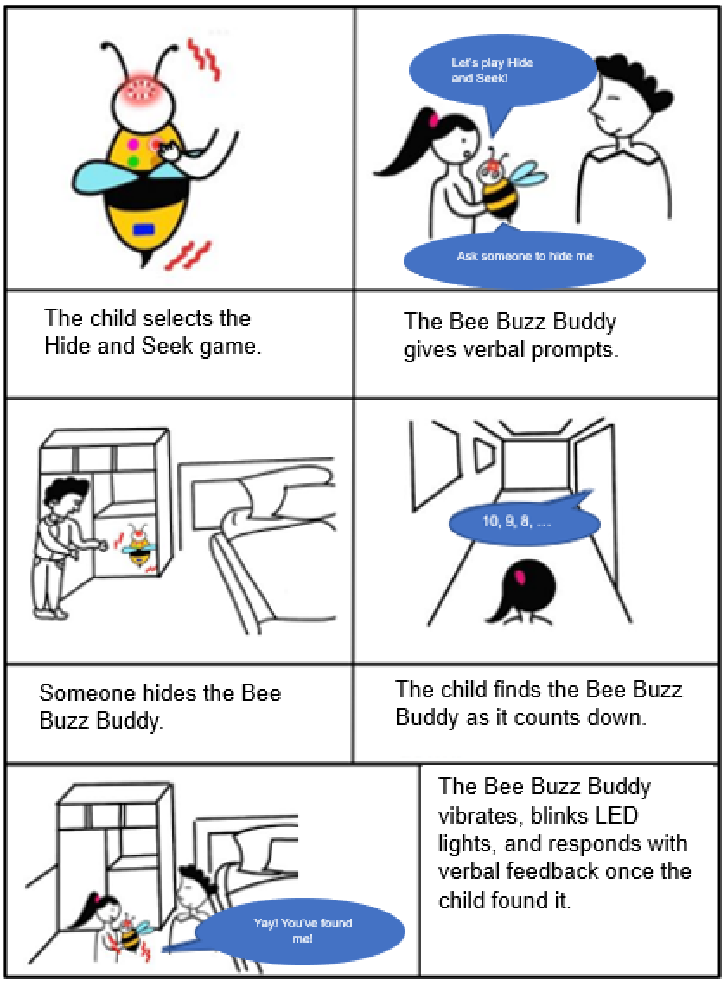


Figure 8: Storyboard of Hide and Seek Interaction Scenario

Game 3 Run to the Beat

Run to the Beat aims to help children to practice locomotor skills (i.e., marching, walking, and running), and exploits music to gamify the activity. Figure 9 shows the interaction scenario of this game, where the Bee Buzz Buddy plays music with modulated rhythms, and the child is told to speed up and slow down in order to keep up with the rhythms. This causes the toy to vibrate with each step it registers, encouraging the child to time their footfall with the music. The Neo Pixel LED ring also acts as a "loading bar" in this game (see Figure 6), where the lights build up as the child runs faster and recede when the child slows down. This offers a more straightforward visualisation of children's movement intensity. This is achieved with a similar method to that used in Game 1, with a change in acceleration along the vertical axis used to determine a "footfall event". However, in this instance, the toy looks for the contrary motion in the IMU sensor which occurs when the user's foot hits the ground. Based on these "footfall events", the device then calculates the duration between each footfall to roughly calculate the child's movement intensity.

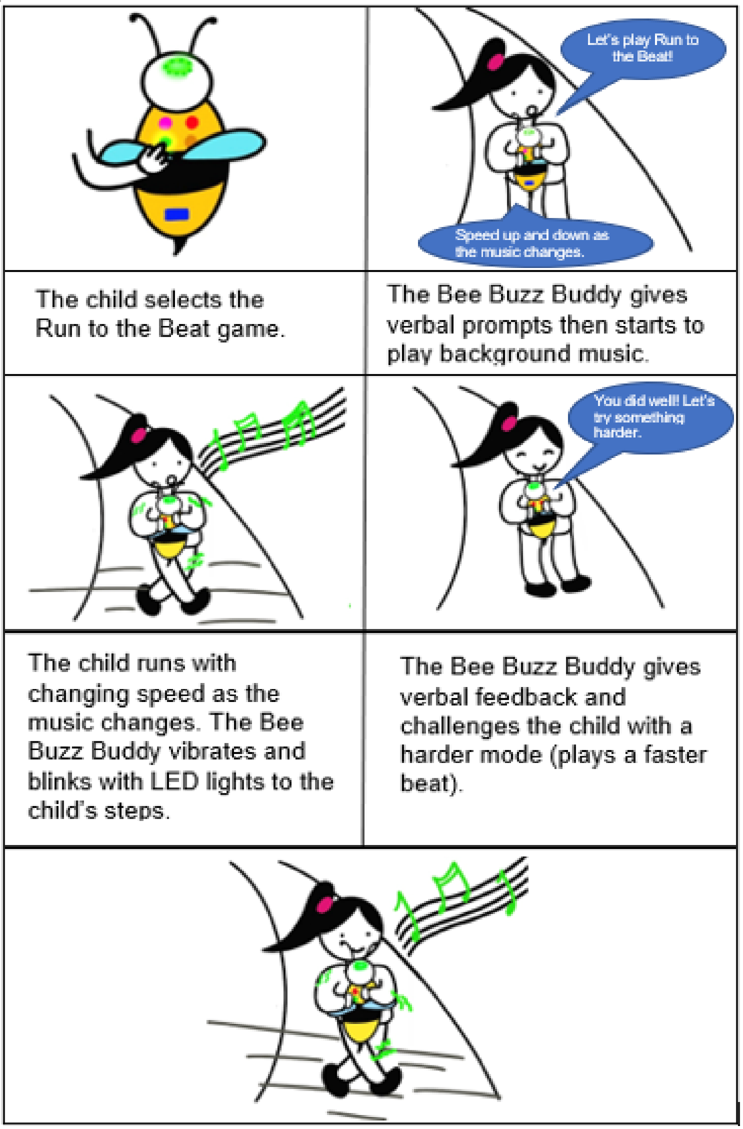


Figure 9: Storyboard of Run to the Beat Interaction Scenario

Game 4 Explore

In the Explore mode, children can play in their preferred ways with any of their preferred toys. This game aims to encourage children's imagination and unstructured free play by prompting them to imagine themselves as a bee and play however they like. Children can also play with their other toys in this mode, where the Bee Buzz Buddy can add another dimension of fun and enjoyment to these toys by providing digital stimuli. When the game begins, the Bee Buzz Buddy is ready to detect any movements of children, and it responds with blinking LED lights and vibrations. It also gives prompts to children if no movements are detected in a certain time. Example prompts include waggling, 'flying', and running in circles like a bee. Explore mode adds to the flexibility of the Bee Buzz Buddy, which makes it suitable to be used in broader play contexts. Figure 10 is an example interaction scenario in the Explore mode.

Figure 10: Storyboard of Explore Interaction Scenario

Testing the Bee Buzz Buddy

The Bee Buzz Buddy prototype is a mediator for us to gather information about children's active play experiences and build our framework. We have been pilot-testing the prototype to ensure it is safe and usable for young children and ready for further studies in lab-based settings and in people's homes.

Pilot Testing and Evaluation of the Initial Design

We conducted a pilot test with the children (4 and 6 years old) of one of the investigators to explore the prototype's usability and the engagement with different game modes. The test went for one hour and it was conducted at the participant's house. The prototype tested was a Bee Buzz Buddy backpack worn by the child (see Figure 11). The test included three games: Animal Jumps (AJ), Hide and Seek (HS), and Run to the Beat (RB). Games were selected by pressing the dedicated button on the backpack strap.

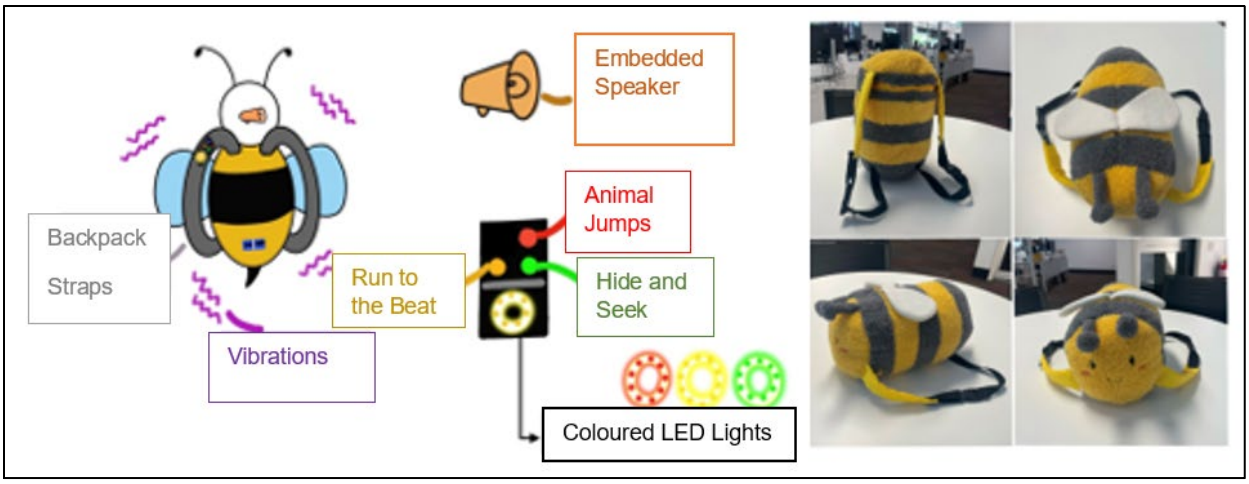


Figure 11 Overview of the Initial Design

The main outcome of the pilot test was to change the design from a backpack to a toy that could be carried. This was because the participant felt uncomfortable wearing the prototype as a backpack and also because the control panel made the straps unbalanced, which meant they could easily fall off. However, the child responded positively to the suggestion to hold or cuddle the Bee Buzz Buddy like a toy.

Looking at our design criteria, we made the following observations during the pilot test:

Flexibility: no space limitations were observed when the participant was engaging in the games. AJ and HS were designed for indoor play, and it was observed that the participant only needed a small space to play the two games. While RB was designed primarily for outdoor play, the participant could still play the game indoors, such as by running in circles. For AJ and RB, the participant played by herself, while she played with her sister for the HS. We did not instruct the participant to use the prototype with other toys, therefore it remained unclear whether the prototype would enhance children's experience with other toys.

Novelty: the prototype successfully encouraged the participant to actively engage in the designed games, especially HS. One researcher hid the prototype in a bathroom, and the participant appeared to be having fun finding the prototype with her sister. The prototype also succeeded in encouraging imagination and imitation, as she attempted to mimic the animals in the AJ game.

Physical Features: the participant found it uncomfortable wearing the prototype primarily due to unbalanced straps and weight of the control box on her shoulder. Additionally, having the control panel on top of a strap unavoidably resulted in wiring difficulties. Potential difficulties include exposed wires, or the wires had to go a long distance inside the bee toy that challenged the enclosure of digital hardware.

Digital Features: the participant showed great interest in the prototype's verbal responses, music, and vibrations, while she found it tricky to see the LED lights on the straps. This is associated to the physical design of the prototype, where the LED lights were placed on the strap at a difficult angle that made it hard to observe while engaging in the activities. We also observed that the verbal responses could be hard to hear, especially with the HS game when the prototype was hidden.

Next Steps of Testing

The pilot test led to the current prototype presented in this paper, which addressed the observed usability issues. The current prototype is ready for rigorous testing, which will include two steps. The first step will be rounds of rapid (10 to 20 minutes) lab-based testing sessions with young children and their parents or caregivers. By combining the user consultation method (Woolner et al., 2007), we will gather target users' reflections and stakeholders' opinions, and the presented prototype will be refined and adjusted to make it robust before being employed as part of a longitudinal study. The second step of testing will be longitudinal over a 6-month evaluation period. This is to test the sustained engagement aspect: whether children remain engaged with the prototype over more than a few hours or days.

Limitations

Limitations of the prototype from the development perspective are primarily about recharging and accuracy of movement detection. In terms of recharging, users will have to open the device, remove, and recharge the batteries regularly over the research period. The inconvenience of recharging could potentially become a dis-engagement factor. Additionally, the prototype could not always detect children's actions accurately considering the potential complexity of their bodily movements as they participate in the activities. The inconsistency of movement detection of the prototype may result in absence of feedback to children's actions. Lack of feedback could also result in dis-engagement during the longitudinal study.

Conclusions and Future Work

In this paper we have presented the design of the Bee Buzz Buddy prototype, a digital toy that provides opportunities for preschool children to engage in active play through games. It is designed as part of a larger study. The study aims to establish a framework for designing TEIs to increase and sustain preschool children's engagement in active play. The prototype will be used as a tool to gather information and help us to build the framework.

The Bee Buzz Buddy prototype blends imaginative play and active play, to benefit children's physical, social, and communication development. It is designed with four games that specifically target preschool children's developmental capabilities, which require children to utilise their senses to communicate and complete the activities. With minimal communication, the prototype conveys prompts and feedback via sounds, music and songs, lights, and vibrations. Additionally, these prompts and feedback respond directly to children's bodily movements. This addresses our previous finding that providing direct and specific feedback to children's physical movements is vital for a TEI to effectively promote active play among young children. We highlight an opportunity for future development of the Bee Buzz Buddy by adding a social dimension. By employing a beehive metaphor, the Bee Buzz Buddy can be further adjusted to be used by multiple children. This will uncover numerous new interaction scenarios for social play.

Acknowledgements

This research was funded by the Australian Research Council (grant DP200100723). The authors would also like to acknowledge and thank Dr Abbe Winter for editing this paper and Hannah and Julia for participating in testing.

References

ACT Government (2020). Active Play | Health. https://www.health.act.gov.au/about-our-health-system/healthy-living/kids-play-active-play/active-play/benefits-physical-activity

Ardevol, E., Lanzeni, D., & Pink, S. (2016). Digital Materialities; Design and Anthropology

Blackler, A., Zelenko, O., Chamorro-Koc, M., Rittenbruch, M., & Sade, G. (2018). Design Research: Methodological Innovation Through Messiness. In M. Filimowicz & V. Tzankova (Eds.), New Directions in Third Wave Human-Computer Interaction: Volume 2—Methodologies (pp. 131–154). Springer International Publishing. https://doi.org/10.1007/978-3-319-73374-6_8

Brockman, R., Jago, R., & Fox, K. R. (2011). Children's active play: Self-reported motivators, barriers and facilitators. BMC Public Health, 11(1), 461. https://doi.org/10.1186/1471-2458-11-461

Cammisa, M., Montrone, R., & Caroli, M. (2011). Development and results of a new methodology to perform focus group with preschool children on their beliefs and attitudes on physical activity. International Journal of Pediatric Obesity, 6(S2), 22–27. https://doi.org/10.3109/17477166.2011.613658

Canning, N. (2020). Children's Empowerment in Play: Participation, Voice and Ownership. Routledge. https://doi.org/10.4324/9780429452178

Cardoso, J. C. S., & Ribeiro, J. M. (2021). Tangible VR Book: Exploring the Design Space of Marker-Based Tangible Interfaces for Virtual Reality. Applied Sciences, 11(4), Article 4. https://doi.org/10.3390/app11041367

Cross, N. (2006). Designerly Ways of Knowing. In Designerly Ways of Knowing (pp. 1–13). Springer. https://doi.org/10.1007/1-84628-301-9_1

Desai, S., Blackler, A., & Popovic, V. (2019). Children's embodied intuitive interaction—Design aspects of embodiment. International Journal of Child-Computer Interaction, 21, 89–103. https://doi.org/10.1016/j.ijcci.2019.06.001

Duncombe, R. (2019). The Physical Development Needs of Young Children. Routledge. https://doi.org/10.4324/9780429469831

El'Konin, D. B. (1999). The Development of Play in Preschoolers: Roles and pretend situations: Their significance and the motivation of play activity. Journal of Russian & East European Psychology, 37(6), 31–70. https://doi.org/10.2753/RPO1061-0405370631

Frauenberger, C. (2020). Entanglement HCI The Next Wave? ACM Transactions on Computer-Human Interaction, 27(1), 1–27. https://doi.org/10.1145/3364998

Gibson, J. J. (2014). The Theory of Affordances. In The Ecological Approach to Visual Perception. Psychology Press.

Goodway, J. (2021). Understanding motor development: Infants, children, adolescents, adults (Eighth edition.). Jones & Bartlett Learning.

Harris, F. (2018). Outdoor learning spaces: The case of forest school. Area, 50(2), 222–231. https://doi.org/10.1111/area.12360

Hesketh, K. R., Lakshman, R., & van Sluijs, E. M. F. (2017). Barriers and facilitators to young children's physical activity and sedentary behaviour: A systematic review and synthesis of qualitative literature: Barriers and facilitators to preschoolers' activity. Obesity Reviews, 18(9), 987–1017. https://doi.org/10.1111/obr.12562

Hornecker, E. (2011). The role of physicality in tangible and embodied interactions. Interactions, 18(2), 19–23. https://doi.org/10.1145/1925820.1925826

Hornecker, E. & Buur, J. (2006). Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. 437–446.

Howard, J. (2013). The essence of play: A practice companion for professionals working with children and young people. Routledge.

Leal Penados, A., Gielen, M., Stappers, P.-J., & Jongert, T. (2010). Get up and move: An interactive cuddly toy that stimulates physical activity. Personal and Ubiquitous Computing, 14(5), 397–406. https://doi.org/10.1007/s00779-009-0270-3

Leonardi, P. M. (2010). Digital materiality? How artifacts without matter, matter. First Monday, 15(6). https://doi.org/10.5210/fm.v15i6.3036

Lillard, A. S. (1993). Pretend Play Skills and the Child's Theory of Mind. Child Development, 64(2), 348. https://doi.org/10.2307/1131255

Lynch, S., Pike, D., & à Beckett, C. (Eds.). (2017). Multidisciplinary Perspectives on Play from Birth and Beyond (Vol. 18). Springer Singapore. https://doi.org/10.1007/978-981-10-2643-0

McNeill, J., Howard, S. J., Vella, S. A., & Cliff, D. P. (2020). Compliance with the 24-Hour movement guidelines for the early years: Cross-sectional and longitudinal associations with executive function and psychosocial health in preschool children. Journal of Science and Medicine in Sport, 23(9), 846–853. https://doi.org/10.1016/j.jsams.2020.02.011

Pakarinen, A., Hautala, L., Hamari, L., Aromaa, M., Kallio, H., Liuksila, P.-R., Sillanpää, M., & Salanterä, S. (2020). The Association between the Preference for Active Play and Neurological Development in Toddlers: A Register-Based Study. International Journal of Environmental Research and Public Health, 17(7), 2525-. https://doi.org/10.3390/ijerph17072525

Pellegrini, A. D., & Smith, P. K. (1998). Physical Activity Play: The Nature and Function of a Neglected Aspect of Play. Child Development, 69(3), 577–598. https://doi.org/10.1111/j.1467-8624.1998.tb06226.x

Pellis, S. M., & Pellis, V. C. (2007). Rough-and-Tumble Play and the Development of the Social Brain. Current Directions in Psychological Science, 16(2), 95–98. https://doi.org/10.1111/j.1467-8721.2007.00483.x

Rao, Z., & Gibson, J. L. (2021). You Pretend, I Laugh: Associations Between Dyadic Pretend Play and Children's Display of Positive Emotions. Frontiers in Psychology, 12, 669767. https://doi.org/10.3389/fpsyg.2021.669767

Sawyer, J. E., & Brooks, P. J. (2021). Sociodramatic play enhances preschoolers' private speech and motivation across activities. Cognitive Development, 59, 101073. https://doi.org/10.1016/j.cogdev.2021.101073

Seo, J., Arita, J., Chu, S. L., Quek, F., & Aldriedge, S. (2015). Material Significance of Tangibles for Young Children. TEI 2015 - Proceedings of the 9th International Conference on Tangible, Embedded, and Embodied Interaction, 53–56. https://doi.org/10.1145/2677199.2680583

Sutton-Smith, B. (1997). The ambiguity of play. Harvard University Press.

Swift, T. (2017). Learning through movement and active play in the early years: A practical resource for professionals and teachers. Jessica Kingsley Publishers.

Tandon, P. S., Saelens, B. E., & Christakis, D. A. (2015). Active Play Opportunities at Child Care. Pediatrics, 135(6), e1425–e1431. https://doi.org/10.1542/peds.2014-2750

Tarlinton, D., E M Vickery, N., Wang, Y., Knight, L., & Blackler, A. (2022). Identifying Factors of Young Children's Engagement in Active Play. In OzCHI '22: Proceedings of the 34th Australian Conference on Human-Computer Interaction. (In Press)

Truelove, S., Vanderloo, L. M., & Tucker, P. (2017). Defining and Measuring Active Play Among Young Children: A Systematic Review. Journal of Physical Activity and Health, 14(2), 155–166. https://doi.org/10.1123/jpah.2016-0195

U'wais, R., Ploderer, B., & E M Vickery, N. (2021). Exploring the Usage of Digital Technology for Active Play During the COVID-19 Pandemic Among Families with Young Children. 33rd Australian Conference on Human-Computer Interaction, 352–361. https://doi.org/10.1145/3520495.3520506

Vickery, N., Tarlinton, D., Wang, Y., & Blackler, A. (2022). Digital toys as tangible, embodied, embedded interactions. DRS Biennial Conference Series. https://dl.designresearchsociety.org/drs-conference-papers/drs2022/researchpapers/308

Vickery, N., Wang, Y., Tarlinton, D., Blackler, A., Ploderer, B., Wyeth, P., & Knight, L. (2021). Embodied Interaction Design for Active Play with Young Children: A Scoping Review. 33rd

Australian Conference on Human-Computer Interaction, 293–306. https://doi.org/10.1145/3520495.3522701

Wang, Y., E M Vickery, N., Tarlinton, D., Ploderer B., Blackler, A., & Wyeth, P. (2022).Exploring the Affordances of Digital Toys for Young Children's Active Play. In OzCHI '22: Proceedings of the 34th Australian Conference on Human-Computer Interaction. (In Press)

Weisberg, D. S. (2015). Pretend play. WIREs Cognitive Science, 6(3), 249–261. https://doi.org/10.1002/wcs.1341

Wick, K., Leeger-Aschmann, C. S., Monn, N. D., Radtke, T., Ott, L. V., Rebholz, C. E., Cruz, S., Gerber, N., Schmutz, E. A., Puder, J. J., Munsch, S., Kakebeeke, T. H., Jenni, O. G., Granacher, U., & Kriemler, S. (2017). Interventions to Promote Fundamental Movement Skills in Childcare and Kindergarten: A Systematic Review and Meta-Analysis. Sports Medicine (Auckland, N.Z.), 47(10), 2045–2068. https://doi.org/10.1007/s40279-017-0723-1

Woolner, P., Hall, E., Wall, K., & Dennison, D. (2007). Getting together to improve the school environment: User consultation, participatory design and student voice. Improving Schools, 10(3), 233–248. https://doi.org/10.1177/1365480207077846

Yanez-Gomez, R., Font, J. L., Cascado-Caballero, D., & Sevillano, J.-L. (2019). Heuristic usability evaluation on games: A modular approach. Multimedia Tools and Applications, 78(4), 4937–4964. https://doi.org/10.1007/s11042-018-6593-1

Yuehao Wang

Yuehao Wang is a PhD candidate in the School of Design, Faculty of Creative Industries, Education and Social Justice at QUT. She graduated from the University of Queensland in 2020 with a Bachelor of Information Technology (Hons) degree. Her current research interests are novel digital technologies for children, particularly tangible, embedded, and embodied interaction (TEI) systems, and how they can be better designed to engage children in physically active play.

James Dwyer

James Dwyer is an accomplished MPhil graduate from the BMW Group and QUT Design Academy, where his research focused on advancing human-robot interactions through communication methods based on social cue theory. Before embarking on his research journey, he obtained an Honours degree in Industrial Design and a Bachelor of Psychology. Currently, James holds the position of Senior Research Assistant at the QUT Design Lab, contributing to projects in the areas of transportation and health, while also tutoring Industrial Design units with an emphasis on tangible interactions.

Having a strong background in prototyping and coding, James has been involved in numerous high-profile projects, such as the HEAL project which received two 2021 Good Design Australian awards and the 2021 QUT Vice-Chancellor's Awards for Excellence (VCAE). He also took on the role of Creative Lead for the Soundline Projects at the ARS Electronica Futurelab, which became a finalist in the 2018 IxDA Awards. James now aims to apply the knowledge and expertise he has gained from these experiences to novel prototyping approaches in human-robot interaction and collaboration as part of his PhD research with the Australian Cobotics Centre.

Nicole E.M. Vickery

Nicole Vickery is a Lecturer of Interaction Design in QUT's School of Design. Inspired by her background in games research and design, Vickery's interests lie in exploring playful interactions with digital technology. Her current research examines how tangible, embodied, and embedded technologies can be designed to encourage children to engage in active play and nature-based play.

Bernd Ploderer

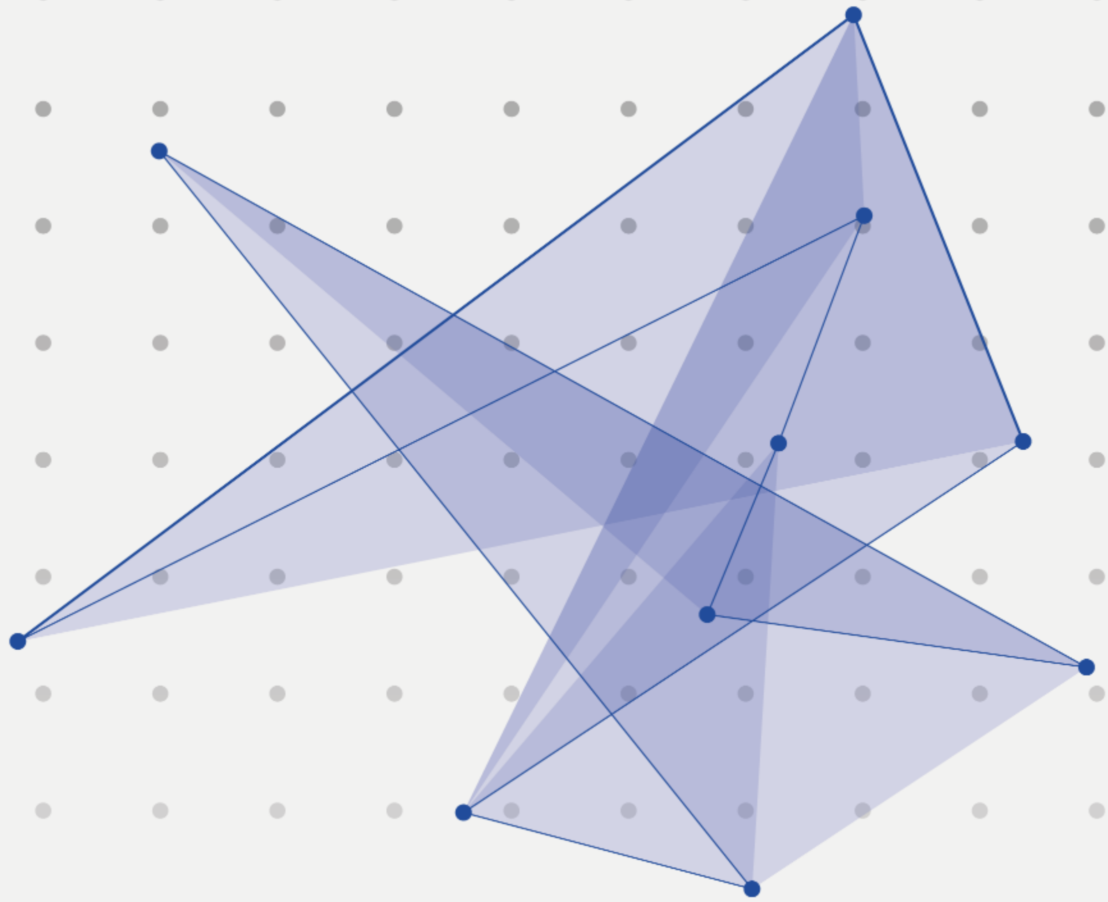
Dr Bernd Ploderer is a Human-Computer Interaction researcher at QUT. Working primarily in health and wellbeing domains, Dr Ploderer studies, designs, and evaluates interactive technologies to help people make sense of data about themselves and the world around them. He leads the Digital Wellbeing Lab at QUT, which envisages a future where all digital technology is designed in partnership with communities for their social, mental, and physical wellbeing.

Dannielle Tarlinton

Dannielle Tarlinton is a PhD Candidate in the School of Design, Creative Industries Faculty at QUT. Tarlinton's current research investigates how people use digital technologies and systems that incorporate tangible, embedded, and embodied interactions (TEIs). She is particularly interested in understanding people's experiences of, and engagement with, such novel digital technologies, which could be used to better inform their design and development.

Alethea Blackler

Alethea Blackler is Associate Dean (Research) of the Faculty of Creative Industries, Education and Social Justice, and a Professor in the School of Design, at QUT. Prof. Blackler is one of the world leaders of research in intuitive interaction, with a book, many articles, and a special journal issue on the topic. She has conducted research projects on intuitive interaction for adults, older adults, and children, developing novel methods of coding observational data in the process. She is also researching how older people engage with technology and how to design for people living with dementia. She is currently leading an Australian Research Council (ARC) Discovery project on novel technologies for increasing active play for preschool children. She has attracted and worked with external partners in government, community and industry on various projects and has won three ARC grants. She has published more than 100 peer reviewed papers, been invited to give presentations internationally, and she is the recipient of several awards, including a 2018 ig-nobel.



Track 2: Service design and Policy making

- Prototyping for Policy Making: Collaboratively Synthesizing Interdisciplinary Knowledge for Climate Neutrality

- The hidden arena: prototyping as a political experience of design

- Oxymoron in Prototyping Digital Artifacts: Reviews of Digitalised Product-Service System (DPSS) Development Projects of Global Tech Companies

- Design prototyping for public technological solutions as a social learning practice for policymaking

- Prototyping in service design: the case of CHECKD. - an automatic booth for Covid-19 testing

Prototyping for Policy Making: Collaboratively Synthesizing Interdisciplinary Knowledge for Climate Neutrality

Sabrina Bresciani, Politecnico di Milano
Cyril Tjahja, TNO
Tamami Komatsu, Politecnico di Milano
Francesca Rizzo, Politecnico di Milano

Abstract

Cities around the world are confronted with the unprecedented grand challenge of reaching carbon neutrality. Policymakers need support in translating the abstractness and complexity of the net zero goal into concrete actions. A prototype has been developed to support urban policy makers in understanding, selecting and tracking the implementation of social innovation approaches as levers to reach climate neutrality. The creation of the prototype develops new knowledge by synthetizing contributions from academic literature, case studies, and experts' opinion, based on cities' needs, and is embodied into an interactive tool of social innovation actionable pathways for climate neutrality. Testing the prototype with policymakers provided insight into cities' envisioned interaction with the tool, leading to the redesign of the prototype into a more engaging interactive tool, and an integrated approach with more technical solutions. The developed prototype categories were based on a synthesis of scientific articles, and bottom-up information from 36 practice-based cases of social innovation for climate neutrality. The design and development of the prototype of the social innovation actionable pathways tool has been informed by the analysis of cities' needs conducted within the NetZeroCities project, which supports 112 European cities in reaching climate neutrality by 2030. A team of experts aggregated the large amount of information derived from literature, cases and users' needs into a pathway and visualized it in an interactive diagram, with the aim to support strategic decision making at urban level, by lowering information overload, providing visual guidance. The testing phase results provided further knowledge: a more engaging visual tool was perceived by policymakers as valuable to start considering social innovation actions in their cities' policies, due to the scarcity of policy makers' time and understanding of social innovation's contribution to climate neutrality. Interaction design could support policymakers in better strategizing.

Social Innovation; NetZero; Knowledge Visualization; Interactive Design; City

Designing services to support policymaking and the development of urban action plans has the potential to provide a relevant impact on shaping how the future could be. Politicians and policymakers are confronted with the complexity of grand challenges, in particular the urgent need to reduce carbon emissions. The EU-funded project *NetZeroCities* aims at supporting 112 European cities to reach climate neutrality by 2030. Going beyond the assumption that technological solutions alone can lead to net zero, the project focuses on important levers of change, such as governance and social innovation. It well established in academic literature that innovation in social practices is an important and necessary component of reaching carbon neutrality (Chilvers & Longhurst, 2016; Angelidou & Psaltoglou, 2017; Hoppe & De Vries, 2019; Ostfeld & Reiner, 2020; Andion et al., 2021; Creutzig, Niamir, Bai et al., 2022). Furthermore, sustainable development needs collective action and systemic innovation (Diepenmaat, Kemp & Velter, 2020). Beyond a restricted focus on acceptance and behavioral change, social innovation can activate citizens to contribute to climate neutrality (*Schönwälder, 2021)*, in particular in reducing Scope 3 emissions. In a systematic literature review on the contribution of social innovation to climate neutrality (Bresciani, Rizzo & Deserti, 2022), 267 scientific articles were identified that provide evidence of the contribution that innovative social practices have to lower carbon emissions as well as contributing to wellbeing (*Engelbrecht, 2018*). Yet, this rich body of academic knowledge does not seem to be systematically deployed by policymakers.

Social innovation initiatives led by citizens that aim to lower emissions are proliferating, from sharing assets to creating energy communities, and from developing peer-to-peer education on reducing the energy consumption at home, to developing certifications of climate friendly business approaches. An extensive review of such cases has been developed within the NetZeroCities project (Bresciani, Rizzo & Deserti, 2022; Mureddu & Bresciani, 2023), with the identification and description of 36 case studies at different scales, including bottom-up citizens-led initiatives as well as top-down political choices, and policies for supporting the emergence and scaling of social innovations aimed at climate neutrality. However, an investigation of social innovation action plans at global level returned only a handful of cities and regions (Taiwan, Montreal, British Columbia), which possess a social innovation action plan. Furthermore, these plans are not specifically focused on climate neutrality goals.

Can design support policymakers and politicians in understanding available knowledge from academic literature and existing cases? And could the act of prototyping together support the development of social innovation acts that can serve as a lever for reducing carbon emissions?

In order to address this pragmatic need, a prototype of an online service was developed for cities, which aims to provide a user-friendly and actionable aggregation of extant knowledge which could support policymakers in developing informed plans urban level. In doing so, facilitating the creation of favorable ecosystems that could support the emergence and scaling of social innovation initiatives (Terstriep, Rehfeld & Kleverbeck, 2020). Prototyping the service according to the principles of clear communication (Bischof & Eppler, 2011), and the known benefits of knowledge visualization (*Bertschi et al., 2013*) contributes to theory development by investigating how complex, vague and scattered knowledge can be aggregated in a visual and cognitively efficient format, making it pragmatically useful for cities.

The results of the prototype testing with policymakers not only advances the development of the interactive tool, but also theoretical knowledge, as implicit assumptions are exposed through the experiential interaction with the prototype, thereby generating new knowledge on unexpressed users' needs (*Valentine, 2013).* For example, the potential benefits of renaming "social innovation for climate neutrality" into "people-based solutions", and the creation of visually attractive interfaces for policymakers.

Furthermore, the act of collaborative prototyping, a user-centered service based on interdisciplinary knowledge (Bogers, & Horst, 2014), enabled the exploration of the interconnections between the three fields of social innovation, policy making and sustainability (Groth et al., 2020).

Prototyping as Knowledge Generation

Based on a series of co-design workshops which took place within the NetZeroCities project, users expressed the need for a service that could provide solid guidance to policymakers and stakeholders in understanding the potential actions that a city could take to support social innovation initiatives. Specifically, users need guidance in developing and scaling of social innovation initiatives aimed at climate neutrality, based on their current level of readiness or contextual factors. Contextually, cities (as well as the government and funding bodies including the European Union) also face the need to measure the effectiveness of the actions and policies they develop. Therefore, the service should include both a planning and an assessment component.

In order to develop such a service, labelled *social innovation actionable pathways*, a sprint was organized with a multidisciplinary group of social innovation experts from different organizations to develop and test a prototype. The group of experts was composed by the first three authors (all of whom have a background in design and social innovation), an expert of democracy and social innovation from Southern Europe, an expert of policies and social innovation from Northern-Europe and a smart cities expert from a Northern European technological university. The methodology adopted for the development of the prototype of the service was the following: firstly, users' needs were analyzed (based on two deliverables of the NetZeroCities project) in terms of cities' expectations for social innovation and action plans. Secondly, insights from a literature review on the contribution of social innovation to climate neutrality (Bresciani, Rizzo & Deserti, 2022), EU-funded projects on the topic, the theory of change developed in the NetZeroCities project (Chaudary, Hawkins & Alvial Palavicino, 2022) as well as data from the 36 cases developed within the project (Romero et al., 2023), were aggregated in a shared online platform. The experts met in three workshops to design the user-centered service, during which the abovementioned insights were synthesized in meaningful categories.

This process of knowledge aggregation went through multiple steps and visual formats (Fig 1-2), comparing multiple criteria and frameworks (including the guide to scaling social innovation developed by the Schwab Foundation and the World Economic Forum (2013), Social Entrepreneurship Ecosystem Assessment developed by the European Commission and OECD[1], and the categories determined within the NetZeroCities project). All experts were involved in providing input and co-creating the categories during the process.

[1] https://betterentrepreneurship.eu/en/node/802

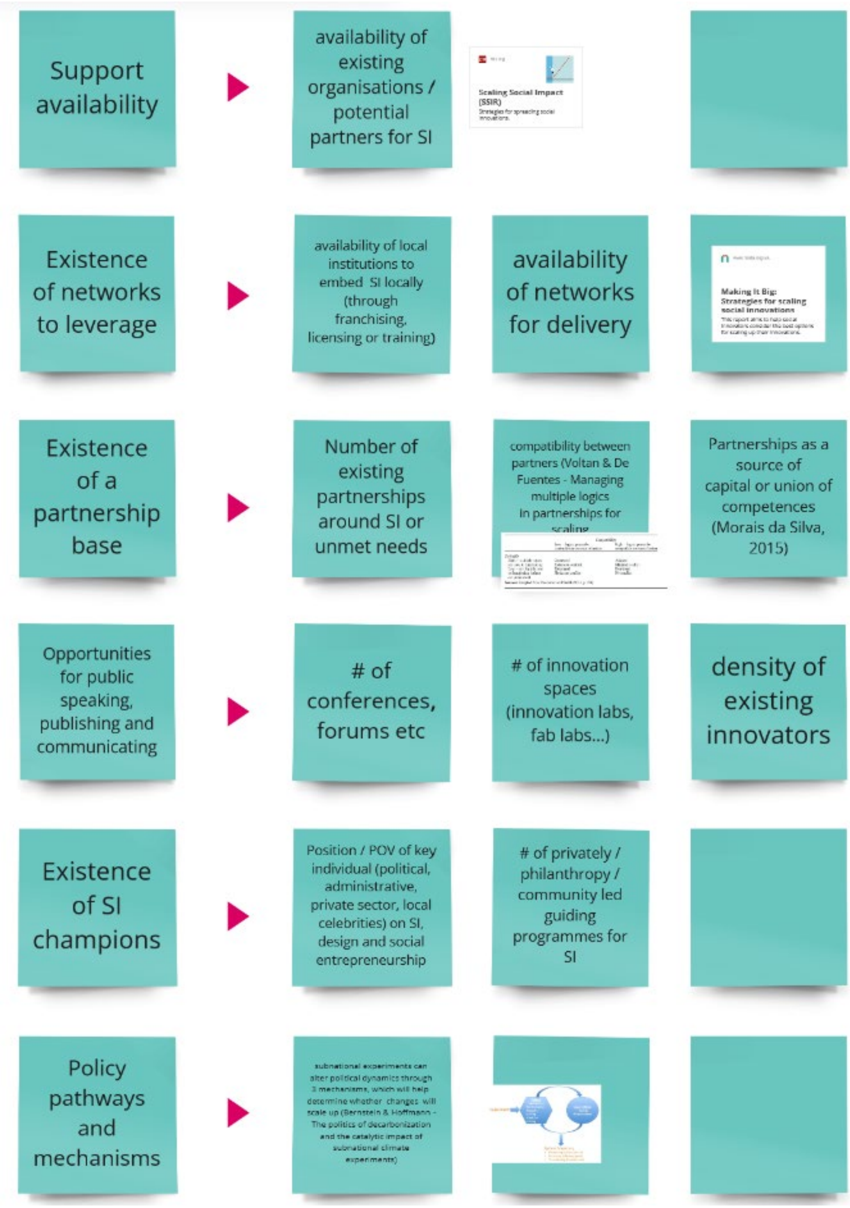


Figure 1: An example of how the knowledge was aggregated and categorized.

Starting from the cities' policymakers' needs, a prototype was developed, deploying the principles of visual and clear communication, in that it should (1) be concise, (2) have a logical structure, (3) have explicit content, (4) be low in ambiguity, (5) and ready to use (Bischof & Eppler, 2011). In addition, visualizing knowledge provides several advantages (Bertschi et al., 2011): it lowers information overload (Eppler, 2006), thus improving the quality of strategizing (Eppler & Platts, 2009), and increases understanding and recall (Bresciani et al., 2011). Specifically for the prototyping of the service, visualizing the synthesis and aggregation of knowledge provides not only a provides a cognitively efficient interface, but also a new theoretical framework of social innovation actions at urban level which can support climate neutrality. Secondly, the prototype links actions to measurement of outputs and outcomes of each proposed action, therefore linking social innovation actions to relevant indicators derived from the literature.

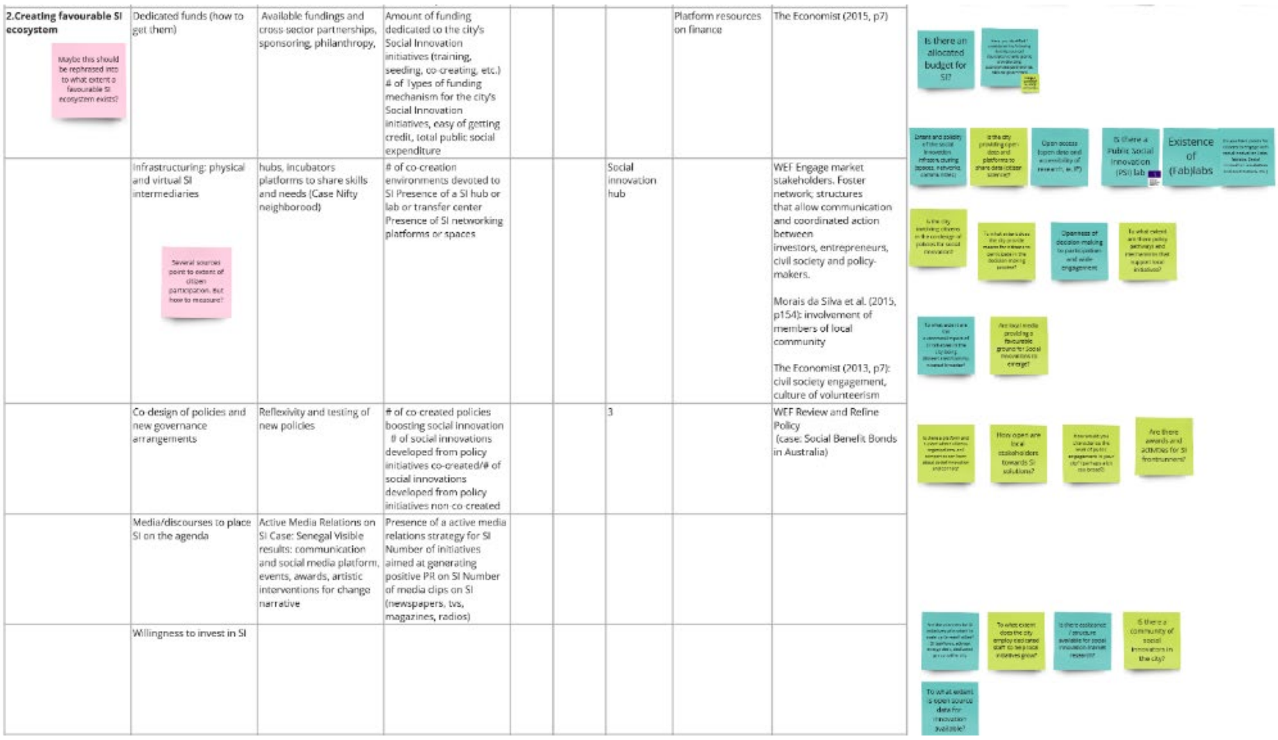


Figure 2: An extract of the collaborative board utilized for the classification of cases, scientific literature and policy articles according to categories.

The first version of the prototype (Fig. 3) is visualized as a timeline composed of 14 categories along three subsequent steps of a pathway: *prepare, act and accelerate* (based on the categories of the City Climate Planner Program developed by ICLEI[2]). Clicking on each category, a box with additional information opens, outlining specific actions, indicators (which are related to SDG goals), and academic references on which the claim is based on. This first rough prototype was presented to a larger group of experts on social innovation, carbon transitions and policy making, within the NetZeroCities consortium. Their feedback was integrated into a more visually appealing and visually coherent prototype (in which all categories had the same size), which resulted into the development of two alternative prototypes to be presented to users.

More specifically, two customer journeys were envisioned (according to traditional categories, which include user actions, user needs, user emotions and touchpoints), leading to the same core visualization of the service. In the first option, the user (which is the city's transition team, as well as policy makers, politicians, etc.) would first answer a questionnaire to gather information on the city's current status, and based on the questionnaire results the online service would automatically highlight suitable next actions. In addition, the system would provide a visual benchmark in the format of yellow stars (1, 2 or 3 stars) to show the performances of a city for each category (see Fig. 4). In the second option, users would directly access the overall interactive map (Fig. 4), and could click on each category and optionally answer the indicators' questions.

[2] https://cityclimateplanner.org/resources

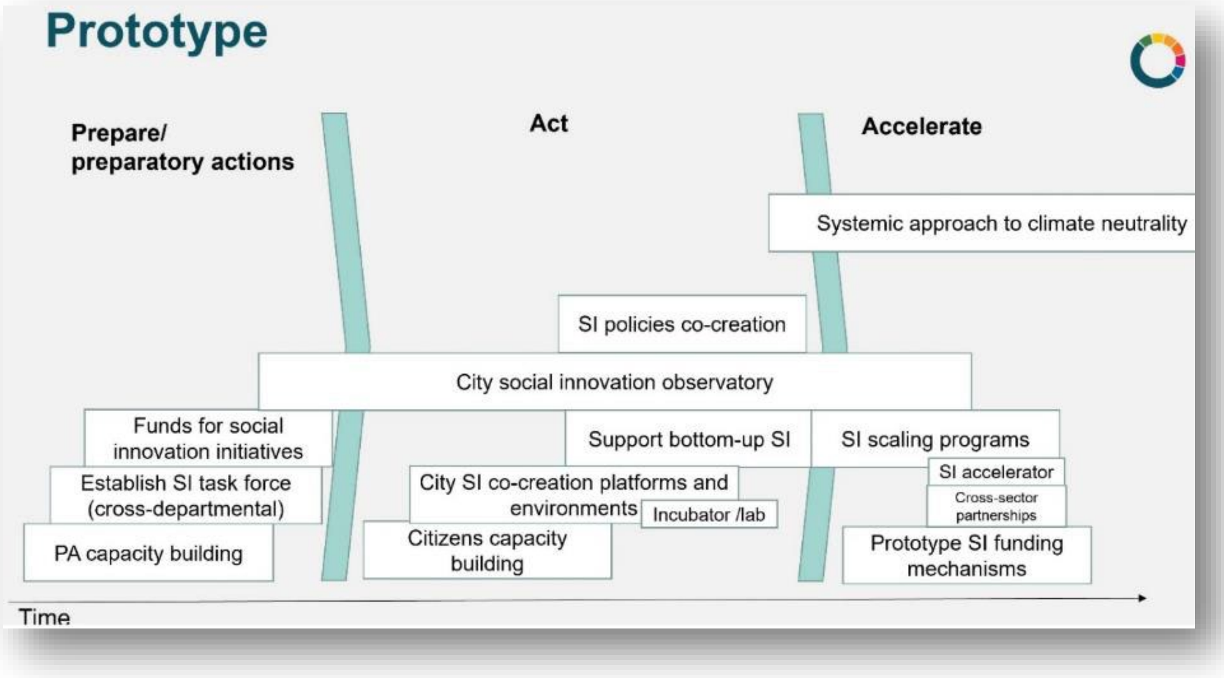


Figure 3: First version of the prototype with categories of social innovation actions for climate neutrality.

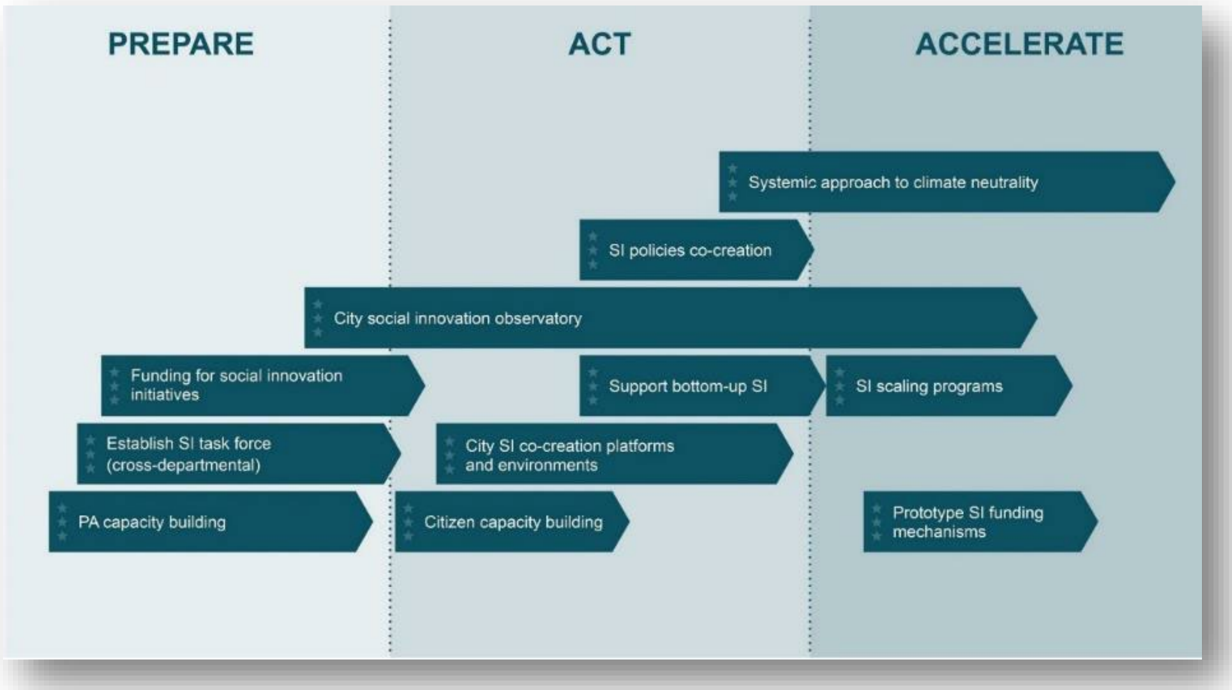


Figure 4: Second version of the prototype: after answering a questionnaire, users can see an overview of the categories and their own scores (visualized as stars for each category).

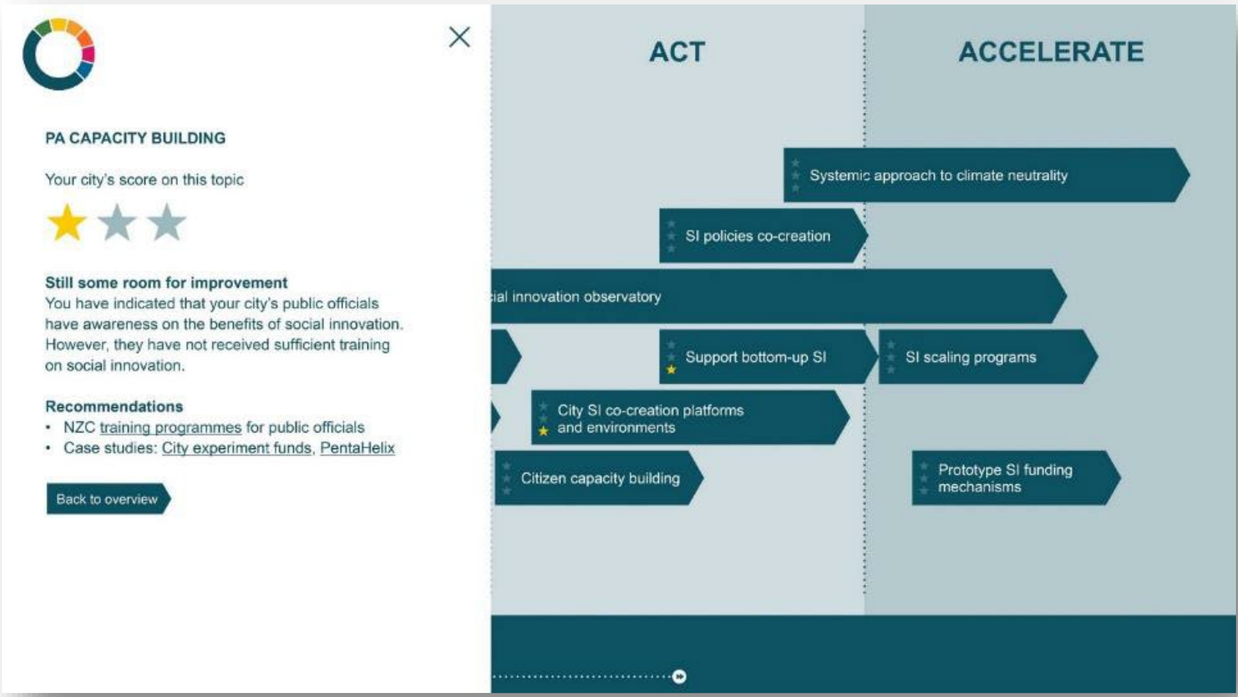


Figure 5: Second version of the prototype: content can be freely explored and optionally integrated by answering questions related to indicators for tracking progresses.

Although the interactive map remains the same, the user journey is different: in the first version, users have to answer a questionnaire to be able to access the map and have customized suggestions of actions to take based on their social innovation readiness.

Insights from Testing and Redesign

To test the prototypes (Fig. 4 and 5), a panel with cities' policy makers was organized online. The participants were three members from the transition teams of their respective cities, which all were small/medium-sized Southern European cities.

Although the participants were willing to use the tool in an explorative way if it did not take too much effort to learn how to use it, they indicated that the connection between social issues and climate neutrality was not evident, and not a priority for their cities. Furthermore, they did not seem to have an accurate understanding of what was meant with 'social innovation'. In addition, they voiced their concern regarding the difficulty in getting the buy-in of the city administration in general on climate neutrality or sustainability, thus needing to link actions to politically relevant and easily communicable topics, such as citizens wellbeing. However, the participants were interested to know how their city is performing compared to other cities in their respective countries and in Europe, and which other cities have already implemented which actions. Finally, a relevant point raised was regarding the language in which the tool would be delivered, which would have to be the local language, as not all politicians and policymakers are comfortable with using English.

The users' feedback was relevant for theory development: contextual factors, such as political commitment and language skills, could prevent the use of the service. In practical terms, the prototype could be improved by including a mobilization phase to convey the relevance of social innovation for the reduction of carbon emissions, perhaps by renaming "Social Innovation for Climate Neutrality" into "People-based Solutions" to align terminology with Nature-based Solutions (Cohen et al., 2016; Faivre et al., 2017). This assumption would need testing before implementation.

From the two options tested, it seems that starting the interaction with a questionnaire would create a barrier, and thus prevent users from using the service, since they do not necessarily understand its value upfront. Therefore, providing a more playful visual interactive infographic without overwhelming potential users seems a suitable user-centered option, as this allows cities to explore the categories in an interactive format, answering the associated questions and tracking their progresses over time. This coincides with the *information seeking mantra*, which is the notion that knowledge is navigated and explored by providing overview first, then zooming into specific topics and further details on demand, (Shneiderman, 2003).

Finally, emphasizing the politically relevant benefits would be useful for engaging politicians in utilizing the tool to develop the cities' transition/action plans to climate neutrality, complementing technological solutions. To address to this challenge, the service could emphasize the co-benefits of both social innovation and decarbonization in terms of citizens wellbeing and improved quality of life. Cases focused on the communication of the co-benefits should therefore be added as well as indicators related to wellbeing. The data resulting from the indicators should then be visualized in a dashboard in which a city's scores can be compared with the country's average or other European cities.Based on the insights from testing, the customer journey and the prototype of the online service were revised. An interactive prototype was created using Kumu, an online platform specialized in mapping relationships (Fig. 6), enabling the content to be interactively explored to test information seeking behavior and usability. Clicking on one of the green fields loads the related content on the left-hand side of the screen, which contains the description of potential actions cities could take, a list of case studies of cities which already implemented this particular action as well as other relevant resources, suggested indicators and academic references.

The content of the third prototype (Fig. 6) was refined together with social innovation experts from within the NetZeroCities consortium. Since some categories were unbalanced, they were reduced. The content for each category was further linked to resources available on the NetZeroCities platform. Iteratively, new content was added to provide cases and references related to the needs identified in the earlier city panel testing phase (i.e. cases and indicators on co-benefits and communication). In this way, the interactive service helped users to transform abstract concepts into concrete actions.

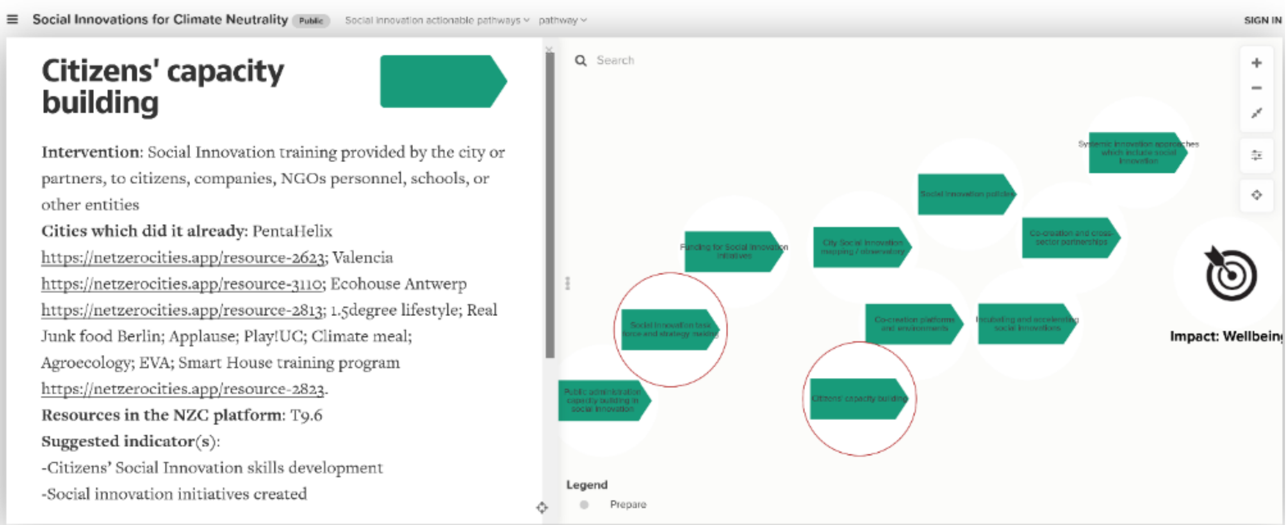


Figure 6: Third version of the prototype: interactive prototype with content on demand.

Implications

Pragmatic Implications

Although several pathways to climate neutrality have been proposed based on technological solutions, to the best of our knowledge, pathways and systematic overviews of how social innovation can contribute to climate neutrality have not yet been conceptualized. The prototype provides a translation of abstract, complex and scattered knowledge into actionable possible futures, and can provide a basis for further improving and testing such synthesis of knowledge.

From a pragmatic perspective, the prototype enables policymakers to support collaborative strategizing on social innovation at an urban level, a tool for informed future making. The testing of the prototype contributes to improving the understanding of policymakers' need for an explorative and engaging modality (Jacob-Dazarola et al., 2020), allowing them to address wicked problems, such as social innovation in climate neutrality. The testing highlighted a misalignment in vocabulary between the (academic) designers and the users, which points to the need of contextualizing the communication of solutions to specific target users.

The creation of the prototype has led to the development of a theoretically grounded and practically relevant framework of potential social innovation pathways to climate neutrality at an urban level. The interactive actionable pathway tool can provide policymakers (deeper) insight into how social innovation can support climate neutrality, and act as a guide to understand the variety of choices available to a city's transition team as well as support the selecting of indicators for learning and measuring progress.

For designers, the methodology deployed for the creation of the prototype can provide guidance to synthetizing academic and pragmatic knowledge into a design outcome. In particular, the prototype serves as a means to surface users' mental models, implicit expectations as well as to envision a novel interactive modality for the target user (in this case, policymakers). In this context, the prototypes become not only a way to design and refine a service, but also an object that supports and mediates the collaborative interaction between diverse actors.

Theoretical Implications

For policymakers, the prototype served as a boundary object (Star & Griesemer, 1989), enabling them to explore the social innovation actions that a city could implement. It also assisted in navigating the content of the NetZeroCities platform to gain more specific knowledge on topics of interest. For researchers, it provided a solid categorization of social innovation practices at an urban level, which are not only built on academic knowledge, but tested in practice-based contexts. The prototype mediated the dialogue (Bojer et al., 2008) and collaboration among researchers, designers, environmentalists, and urban transition teams (*Growth et al., 2020*).

The experiential knowledge acquired while creating, testing, redesigning and retesting the prototype (*Valentine, 2013)*, allowed the development of a more solid theoretical framework, in addition to the practical tool. Through prototyping, the solution and the problem space have co-evolved (Dorst & Cross, 2001), supporting researchers in better refining the theoretical framework, by expanding the problem space to include motivational issue of the users. The prototype also allowed experts from different fields to visually connect their knowledge, exploring new cross-pollinations between social and environmental sciences. The process of collaboratively mapping interdisciplinary knowledge in the prototype is a goal in itself (*Growth et al., 2020),* which gives a tangible form to abstract - often siloed - knowledge.

Conclusion

The methodology for the prototyping provides an example of a successful aggregation of top-down scientific knowledge, bottom-up theorizing from case studies, users' needs and insights from collaboration with interdisciplinary experts and real-life user testing. Yet, this study is not free of limitations; the prototype still needs further refinement and further testing, in particular expanding the sample size, which would allow to account for the influences of contextual factors, such as the size of the city, the political will at urban and national level as well as language and cultural issues. Within the NetZeroCities project, the tool will be further developed and improved, and eventually made available to the 112 cities that are part of the project. In a VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) world, design can provide a methodology to interact with complexity and make ambiguous, abstract knowledge more tractable, envisioning innovative solutions (Cousins, 2018), and imagine possible futures.

We believe the prototyping process enabled researchers to refine a theoretical framework, provided designers with a methodology to an unstructured novel topic, and policy makers with an interactive tool to support strategizing for leveraging people-based solutions for climate neutrality.

Acknowledgements

This project has received funding from the European Commission H2020 Research and Innovation Programme under the grant agreement n°101036519.

References

Andion, C., Alperstedt, G. D., Graeff, J. F., & Ronconi, L. (2021). Social innovation ecosystems and sustainability in cities: a study in Florianópolis, Brazil. Environment, Development and Sustainability, 1-23.

Angelidou, M., & Psaltoglou, A. (2017). An empirical investigation of social innovation initiatives for sustainable urban development. Sustainable cities and society, 33, 113-125.

Bertschi, S., Bresciani, S., Crawford, T., Goebel, R., Kienreich, W., Lindner, M., ... & Vande Moere, A. (2013). What is knowledge visualization? Eight reflections on an evolving discipline. Knowledge Visualization Currents: From Text to Art to Culture, 13-32.

Bischof, N., & Eppler, M. J. (2011). Caring for Clarity in Knowledge Communication. Journal of Universal Computer Science, 17(10), 1455-1473.

Bojer, M. M., Roehl, H., Knuth, M., & Magner, C. (2008). Mapping dialogue. A research project profiling dialogue tools and processes for social change. The German Technical Co-Operation (GTZ) Project: Support to the HIV/AIDS Programme of the Nelson Mandela Foundation, 10. Taos Institute Publications: Chagrin Falls, Ohio.

Bogers, M., & Horst, W. (2014). Collaborative prototyping: Cross‐fertilization of knowledge in prototype‐driven problem solving. Journal of Product Innovation Management, 31(4), 744-764.

Bresciani, S., Eppler, M., Kaul, A., & Ylinen, R. (2011, July). The effectiveness of knowledge visualization for organizational communication in Europe and India. IEEE Proceedings of the 15th International Conference on Information Visualisation (pp. 365-370).

Bresciani, S., Rizzo, F., & Deserti, A. (2022). Toward a Comprehensive Framework of Social Innovation for Climate Neutrality: A Systematic Literature Review from Business/Production, Public Policy, Environmental Sciences, Energy, Sustainability and Related Fields. Sustainability, 14(21), 13793.

Chaudhary, N., Hawkins, P., & Alvial Palavicino, C. (2022). NetZeroCities Theory of Change. Deliverable 2.14. NetZeroCities EU H2020 Grant Agreement n°101036519.European Union, Brussel.

Chilvers, J., & Longhurst, N. (2016). Participation in transition (s): Reconceiving public engagements in energy transitions as co-produced, emergent and diverse. Journal of Environmental Policy & Planning, 18(5), 585-607.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.) (2016). Nature-based solutions to address global societal challenges. IUCN: Gland, Switzerland, 97, 2016-2036.

Cousins, B. (2018). Design thinking: Organizational learning in VUCA environments. Academy of Strategic Management Journal, 17(2), 1-18.

Creutzig, F., Niamir, L., Bai, X. et al. (2022). Demand-side solutions to climate change mitigation consistent with high levels of well-being. Natature Climate Change,12, 36–46.

Diepenmaat, H., Kemp, R., & Velter, M. (2020). Why sustainable development requires societal innovation and cannot be achieved without this. Sustainability, 12(3), 1270.

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem–solution. Design studies, 22(5), 425-437.

Engelbrecht, H.-J. (2018). The (social) innovation – subjective wellbeing nexus: subjective well-being impacts as an additional assessment metric of technological and social innovations, Innovation: The European Journal of Social Science Research, 31(3), 317-332

Eppler, M. J. (2006). Managing information quality: Increasing the value of information in knowledge-intensive products and processes. Springer Science & Business Media.

Eppler, M. J., & Platts, K. W. (2009). Visual strategizing: the systematic use of visualization in the strategic-planning process. Long Range Planning, 42(1), 42-74.

Faivre, N., Fritz, M., Freitas, T., De Boissezon, B., & Vandewoestijne, S. (2017). Nature-Based Solutions in the EU: Innovating with nature to address social, economic and environmental challenges. Environmental research, 159, 509-518.

Groth, C., Pevere, M., Niinimäki, K., & Kääriäinen, P. (2020). Conditions for experiential knowledge exchange in collaborative research across the sciences and creative practice. CoDesign, 16(4), 328-344.

Groth, C., Pevere, M., Niinimäki, K., & Kääriäinen, P. (2020). Conditions for experiential knowledge exchange in collaborative research across the sciences and creative practice. CoDesign, 16(4), 328-344.

Hoppe, T., & De Vries, G. (2019). Social innovation and the energy transition. Sustainability, 11(1), 141

Jacob-Dazarola, R., de Francisco Vela, S., & Rognoli, V. (2020). Affective-Driven Design: Emotions, Moods and Experiences as Catalysts for Socially Meaningful Design. Diseña, (17), 14-25.

Mureddu, F. & Bresciani, S. (2023). Report on Indicators & assessment methods for social innovation action plans. Deliverable D2.7. NetZeroCities EU H2020 Grant Agreement n°101036519. European Union, Brussel.

Ostfeld, R., & Reiner, D. M. (2020). Public views of Scotland's path to decarbonization: Evidence from citizens' juries and focus groups. Energy Policy, 140, 111332.

Romero, S., Sànchez, T., Komatzu Cipriani, T. & Rizzo, F. (2023). Social Innovation for Climate Neutrality. D9.1 NetZeroCities. *EU H2020 Grant Agreement n°101036519. European Union, Brussel.*

Schönwälder, G. (2021). Engaging citizens to boost climate neutrality and greater circularity: opportunities and challenges for research and innovation. Clean Technologies and Environmental Policy, 23(2), 483-489.

Schwab Foundation for Social Entrepreneurship & World Economic Forum (2013). Breaking the binary: Policy guide to Scaling Social Innovation. Schwab Foundation for Social Entrepreneurship, Cologny/Geneva.

Shneiderman, B. (2003). The eyes have it: A task by data type taxonomy for information visualizations. In: The craft of information visualization (pp. 364-371). Morgan Kaufmann.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social studies of science, 19(3), 387-420.

Terstriep, J., Rehfeld, D., & Kleverbeck, M. (2020). Favourable social innovation ecosystem(s)? An explorative approach. European Planning Studies, 28(5), 881-905.

Valentine, L. (Ed.). (2013). Prototype: design and craft in the 21st century. A&C Black.

Sabrina Bresciani
Sabrina Bresciani is a senior assistant professor at the Design Department of the Politecnico di Milano (Italy). Her research focuses on visual design thinking, social innovation and assessment. She has extensive international research experience having lived and worked in 8 different countries in Europe, America and Asia.

Cyril Tjahja
Cyril Tjahja is a researcher at the Dutch research organisation TNO, assistant professor at the Vrije Universiteit Amsterdam, and a design practitioner. His research interests include design and social innovation, co-design, social design, and citizen engagement.

Tamami Komatsu
Tamami Komatsu is a senior researcher at the Department of Design of the Politecnico di Milano (Italy). In her research she aims at finding ways to help public sector organizations harness their potential for change and better use their resources for citizen-led value creation through a human-centered design approach.

Francesca Rizzo
Francesca Rizzo is full professor at the Department of Design of the Politecnico di Milano (Italy). She has extensive experience managing EU-funded research projects and her research focuses on service design for the public sector, co-design and advanced participatory design processes.

The hidden arena: prototyping as a political experience of design

Rose Dumesny, frogLab, frog (Part of Capgemini Invent)
Dorian Reunkrilerk, Co-design Lab and Media Studies, Telecom Paris (IP Paris)

Abstract

With prototyping, design practice thinks about the shape and environment of many objects that will embody our world experiences. In that, we see this action as eminently political and we ask ourselves along this paper the following question : under what conditions can prototyping be a political experience of design? Based on the analysis of three design use cases that present a prototyping situation, this paper explores ways designers could embody the political dimension of their practice. While observing our use case through a framework built from sociology and political science literature, we are looking for signs of politics in our practices of design. This work, part of a more extensive research, shows that prototyping could be the most adapted situation to experience the political in design because it brings together human and non-human actors into a co-design process where debate is necessarily present.

Debate; Political Experience; Arenas; Trouble; Embodiment

Since the 1960s, theories on democracy have tended to represent it as an experience of politics that organizes the life of a society based on a principle of debate. In that, it becomes possible to discuss which pathways to choose for society. Chantal Mouffe (1993) says that this debate doesn't need to reach the idea of consensus but more the one of dissensus, considered as an antagonism and confrontation state, inherent to the act of living together. In relation to this assumption, the introduction of the book "Making Things Public", wrote by Bruno Latour (2005), asks a fundamental question : how is politics embodied today, beyond the official parliaments that seem insufficient to make visible the many ways in which society orients, discusses, and debates its future? In other words, which are the non-dominant arenas that bring to life the political question? Here, Latour underlines that this question is not only valuable for spaces as parliaments, but also in our daily experience of objects.

In this paper we pursue this idea of an object-oriented democracy and consider prototyping as a possibility for design to find specific forms of political experience. With prototyping, design practice thinks about the shape and environment of many objects that will embody our world experiences. In that, we see this action as eminently political and we ask ourselves along this paper the following question: under what conditions can prototyping be a political experience of design?

We begin this paper with the definition of the conceptual framework that supports our positioning. Then we describe a methodology based on three typical use cases of prototyping in design (school, public space, design studio). Finally we analyze them with an analytical grid we build from sociology and political sciences literature. The goal of this analysis is to open perspectives for design practitioners on the political dimension of their practices.

A Political Experience of Design

Since William Morris' thoughts to the Italian Radicals' experimentations, design practices have something to do with politics. But some of them have put the notion of debate at the heart of their practices. Critical Design (Dunne & Raby, 2007) is one of the most famous. This movement, which became Speculative Design later (Dunne & Raby, 2013), carries a critical thinking materially translated by design. The main challenge of this practice is to provoke self-reflexivity about what is self-evident, in order to "challenge narrow assumptions, preconceptions and givens about the role products play in everyday life" (Dunne & Raby, 2007, § 1). The productions of Speculative Design don't come with economically viable solutions but have a role "to act like a mirror reflecting the role a specific technology plays or may play in each of our lives, instigating contemplation and discussion" (Auger, 2012, p. 29).

With other practices, Reflective Design aims to make legible unconscious adoption of object's values and in the meantime engage users to have this same critical thinking (Sengers et al., 2005). Adversarial Design (Carl DiSlavo, 2015) suppose that objects could encourage the identification of society's issues in order to reveal disagreements and allow revendications. Beyond those movements that locate design in a specific field of practices, we would like to observe design politics which describe "ways practices of design and politics, historically and materially, reinforce and legitimize each other" (Keshavarz, 2016, p. 93) in design practices. Keshavarz invites us to work on "ontological conditions of design as an act, and the effects it generates in different environments" (Keshavarz, 2016, p. 86).

This seems to echo the PhD thesis of Max Mollon when he asked: "Hence, if designing is to transform "an existing situation into a preferable one" I wondered for whom are these forms of design preferable? And, how do we enable debate about what is preferable?" (Mollon, 2019, p. 8). His question refers directly to the ways society and politics interfere, and more to the difference between *politics* and *political*. Chantal Mouffe (2005) suggests that the term political refers more to an antagonistic state, inherent to the act of living together. The illusion of consensus needs to be stopped with a new use of debate. Mouffe explains this illusion by the hegemonic position of some stakeholders at the cost of others : "There is no consensus without exclusion of a "third"" (Mouffe, 2005, p. 149). Mouffe also highlights that an antagonistic state could be a possibility of living together by gathering and sharing the conditions of authority. Already in the 14th century, the term debate meant both "to quarrel, to dispute" and "to discuss, to deliberate on the pros and cons of".

It is precisely this question of dissensus that Latour proposes to see as a prerequisite to any thought of politics. To do so, the philosopher calls for an "object-oriented democracy" that questions the way in which political spaces have been organized around objects perceived above all as facts: "For too long, objects have been wrongly portrayed as matters-of-fact. […] They are much more interesting, variegated, uncertain, complicated, far reaching, heterogeneous, risky, historical, local, material and network" (Latour & Weibel, 2005, p. 9-10). People, or their representatives, gather within official spaces of speech where these facts can be debated from a tacit principle of univocal understanding of the facts. However, if we adopt a principle of pluralism, then emerges the figure of the Ding, or the "thing", and replaces at the heart of politics the matter which brings people together because precisely this matter divides them while concerning them. It is this idea that was at the origin of many parliaments throughout the world and that Latour proposes to restore: " If the Ding designates both those who assemble because they are concerned as well as what causes their concerns and divisions, it should become the center of our attention " (Latour & Weibel, 2005, p. 13).

In this paper, we would like to pursue this thought about a *design for debate* (Mollon, 2019) and investigate design situations perceived as ordinary and non-political, where the political experience and the politics of design are made sensitive through debate. By considering debate as the very result of its practice, design for debate emphasizes the importance of an artifact's discursive properties: either the artifact has an internal narrative and carries elements of controversy, or it is the situation in which the artifact is located that will trigger potential controversial discussions (Mollon, 2016). Mollon thus emphasizes the situated nature of the debate, while showing the ineffectiveness of certain practices, when they are only disseminated by exhibitions which "do not encourage people to meet each other, or to meet the author(s), nor do they encourage debate" (Mollon, 2019, p. 116). Therefore, the author proposes a model to analyze the ways in which a project reaches its audiences by participating in a larger system articulating problems, artifacts, mediums and audiences. This model thus makes visible the different levels of influence of the debate within a given situation: from the problem to be addressed, through the type of more or less familiar artifacts and mediums, to the communication channels and institutions symbolically represented.

If organizing a debate is a systemic design situation, we ask ourselves what other design situations could be the scene of political actions. One of the situations we wish to explore is prototyping. Indeed, due to its capacity to gather different actors, i.e. to maintain a dialogical relation in the project (Yu et al., 2018), there is a relative dimension of debate. A prototype thus represents a potential endless space of exploration allowing to discuss design impediments or opportunities. Here, the act of prototyping is perceived as an open space, where the integration of new ideas, materials, references and knowledge allow new directions in the project.

The notion of prototyping is deeply rooted in the practice of design insofar as, through the prototype, the thought of a designer is embodied in a materially defined situation (Gentès, 2022 ; Koskinen, 2010). The prototype thus reminds us of the fundamentally situated practice of design, in constant dialogue with the material elements of the situation (Schön, 1983). The mediums used by designers seem to offer opportunities for the emergence of ideas or "matrices of emergence" (Gentès, 2022, p.62) that give them "meaning after their work and not by following a predetermined idea that would gradually become embodied in artifacts." This idea echoes Gaver et al. 's (2022) proposal to assume emergence as a potentiality of design research and identify strategies to foster this emergence. *Consider anomalies, seek idiosyncratic examples*, *tell the full backstory or value agility and responsiveness* are some of the 12 strategies identified, and encourage thinking about the act of design in the making. The notion of emergence seems to us to relate to prototyping as a situation, going further than simply giving shape to imagined objects.

Therefore, we can think of the act of prototyping as the concrete manifestation of the designers' diagrammatic thinking in that it allows us to describe : “What [designers] work on, in the time of their practice, and which is not yet defined since all their work consists in defining this thing: whether it is an object, an image, a device, an interface, etc., only exists first in a virtualized way by a diagrammatic device constituted by these images that are the prototypes, the plans, the sketches, the procedures, etc." (Beaubois, 2015, p. 56). The design activity is thus composed of a set of interdependent diagrams, or prototypes, which express the object being designed.

Hence, considering a prototype more as a situation than as an artifact makes it possible to extend what the act of prototyping comes to be. Subrahmanian et al. (2003) emphasize that the word prototype can refer to any cognitive structure: verbal, gestural and virtual representations and models, protocols, processes, physical artifacts, etc. This diversity thus leads us to go beyond approaches which describe prototyping as a series of versions whose resolution should be more and more precise (Vinck, Jeantet & Laureillard, 1996).

In this paper, we thus explore what conditions, in a prototype as situation, allows a political experience of design. In other words : what are the conditions that give rise to debate in ordinary design practices, such as prototyping?

The Arena as an Analytical Framework

In order to analyze the conditions of a political experience of design within a prototyping situation, we have voluntarily selected three different situations (Fig.1): a project design course within a design program of a french university (usecase A), a co-design project developed in a neighborhood of a major French city (usecase B) and an ideation workshop in a large company (usecase C). The diversity of these situations allow us to observe different spaces, temporalities, actors, tools, positions and commitments in the designing situation.

Usecase Code	A	B	C
Context	Teaching: project practice course around the notion of translation	Commission: social design project initiated by associations in the Wazemmes district of the city of Lille	Commission : UX design project for a public client by a external design studio
Temporality	12 sessions of 3 hours (50 hours) spread over approximately 8 weeks	3 weeks of immersion in the neighborhood, including a period of preparatory work before the immersion	1 day of workshop (8 hours)
Place	An University	One neighborhood	A company
Participants	5 groups of 2 or 3 third-year design students	Neighborhood citizens, various stakeholders such as elected officials, neighborhood associations	2 groups of 10 employees
Space type	Computer room: lines of non-modular or movable tables, computer stations, whiteboard. No other equipment specific to the practice of the project	The street, the public spaces, a room made available for the project team	A "COMEX" type meeting room, with a big and non-movable table
Prototyping subject	Experimenting with the notion of translation in the project: the subject is to be found by the students	Questioning the feeling of living in the Wazemmes district	Redesigning the client's website
Prototyping activity	Translation of a problematic situation via the creation of 3 mediums exploring differently the situation then translation into a potentially preferable situation by paying attention to the forms of translations to operate	Exploration of the imaginary of the neighborhood (participatory sensitive mapping, interviews, participatory showcase) and potential actions (project sheets, sensitive walk, blank stickers revealing the potential of the neighborhood).	Creation of a functional structure of the future website, from some different functional bricks
Presentation format	2 deliverables: a poster presenting the exploration of the project through the 3 mediums allowing to problematize the subject then, at the end of the course, a file presenting a detailed project proposal	Data collection formats = feedback formats (showcase, project sheet, etc.) but also public exhibition in a neglected area of the neighborhood, meetings with local officials, project booklet available for download	Projection on screen of the functional structure produced during a finale presentation with all participants

Figure 1: Summary presentation of the use cases.

Our analytical framework is based on a two-step process. In the first step, we conducted field observations by focusing on issues raised by Bruno Latour and described earlier. Indeed, pluralism, in terms of viewpoints, actors and their interests, requires considering how an assembly could be constituted. Matters of concern can't be understood, described and debated in the same way in different assemblies. According to Latour, to "speak well of the things" (Latour, 2022) that concern us, involves adopting a triple representation principle: first, to represent the issue that justifies the existence of an assembly. Here, we observed in the situations of prototyping how the first issue raised by the project was materially represented, debated and how it changed according to new issues raised during the situation. Second, to guarantee that the assembly is made up of people who are themselves representative. We mapped all the stakeholders of the situation according to their status outside and inside the situation. Finally, to materially build the assembly that embodies the public emerging from this concern. We observed all the material properties of the situation that allowed actors in the situation to discuss, debate and decide.

In the second step, we analyzed all the collected data in relation to the notion of arena. An arena can be defined as a collective mobilization that emerges when members of an unlabelled group feel concerned by a trouble (Harraway, 2016), define it as a problem and resolve it by taking action (Cefaï, 2016). Using the notion of arena allowed us to refine our analysis from a political perspective. Therefore, this perspective allowed us to analyze data from three different points of view. First, we analyzed what allows a group of people to feel concerned, both collectively and individually by a trouble. We thus seek to grasp the conditions determining both the participants' access to the situation and what they can express themselves on. Second, we analyzed the situations from the point of view of the problem that the public defines collectively. Here, we try to grasp the conditions relative to the mode of confrontation between participants and the material properties of this mode. Finally, collected data were also analyzed from the point of view of what the group agrees to make visible. We seek to capture the conditions of access for other audiences as well as the discourses produced.

Therefore, our two-step analytical framework is built by crossing the conditions of the creation of an assembly and the emergence of an arena (Fig. 2).

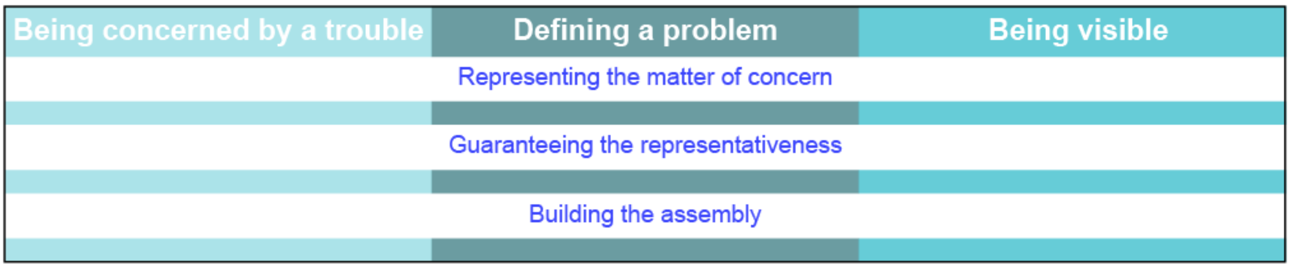


Figure 2: Analytical framework based on a two-step process.

The thematic and comparative analysis of all data we collected through this framework allowed us to grasp the material, spatial, temporal and social properties of prototyping situations from a political point of view. It is important to say that the conditions we describe in the following section were not observed explicitly in all the situations: it is precisely the point of a comparative analysis to be able to bring out more explicitly important elements of analysis.

Emerging Conditions of a Political Experience of Design

In this section we present all the conditions we grasped through our analysis. These emerging conditions can be seen as concrete means of action for designers to develop a political experience within a prototyping situation.They thus underline the importance of being fully conscious of the debate emerging in any prototyping situation and the potential of the emergence of an arena.

As described earlier, this emergence is characterized by the sharing of an experienced trouble, the definition of a problem and the visibility of the constituted arena around this problem. In order to detail them in relation to our field observations, we designed three scenarios (Fig.3, 4, 5) representing these characteristics (through three colors background, more or less present according to our observations) as well as the most important steps of each situation (drawings thus evoke important moments of our observations). The numbers allow us to associate a specific moment we observed with a specific condition.

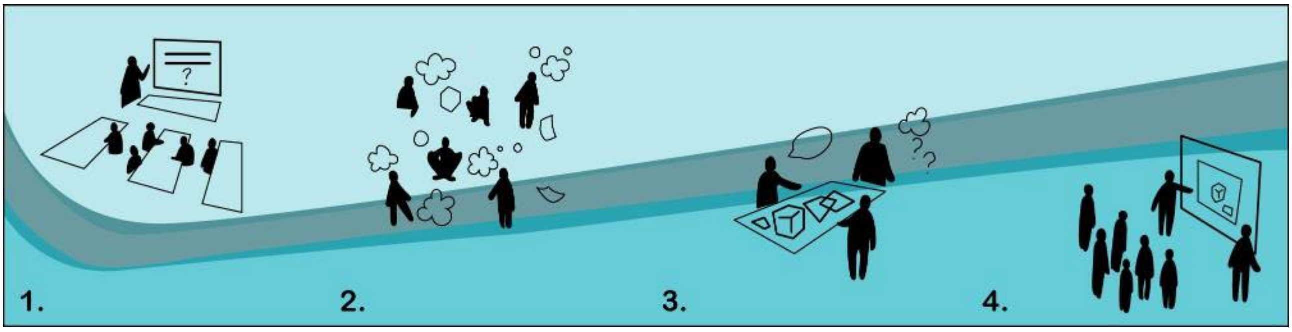


Figure 3: Use case A

1. *Beginning of the project: Students are asked to answer individually to a question (Have you observed or had experiences that you would have wished to translate?) by drawing on their personal experience.*
2. *Divided into groups, students must then collectively find common points to formulate a trouble represented through three specific mediums.*
3. *This trouble is then translated into a problem and explored outside of class time. The time spent with the teacher is used to report on the work done.*
4. *Each group gives a presentation in the classroom to the teacher and the other groups.*

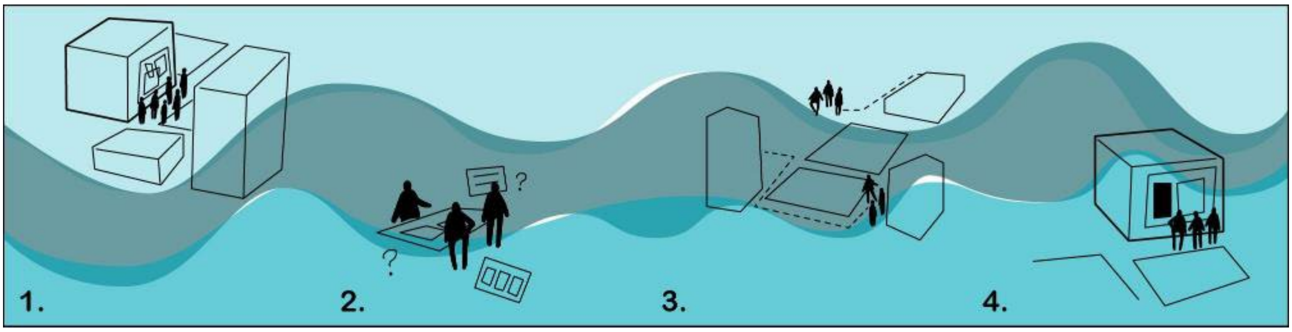


Figure 4: Use case B

1. *A space dedicated to the project is found in the neighborhood. This space allows to propose workshops (but also in other places) inviting inhabitants to express themselves on their perceived images and habits of the neighborhood.*
2. *Ideation workshops are carried out with inhabitants: project templates are distributed in order to collect ideas on possible transformations of the neighborhood.*
3. *Tours of the neighborhood are organized in order to identify places to be changed: stickers are stuck on them by the inhabitants indicating the possible evolutions.*
4. *The data collected is then presented to the inhabitants, directly in the public space, as well as to the local elected officials.*

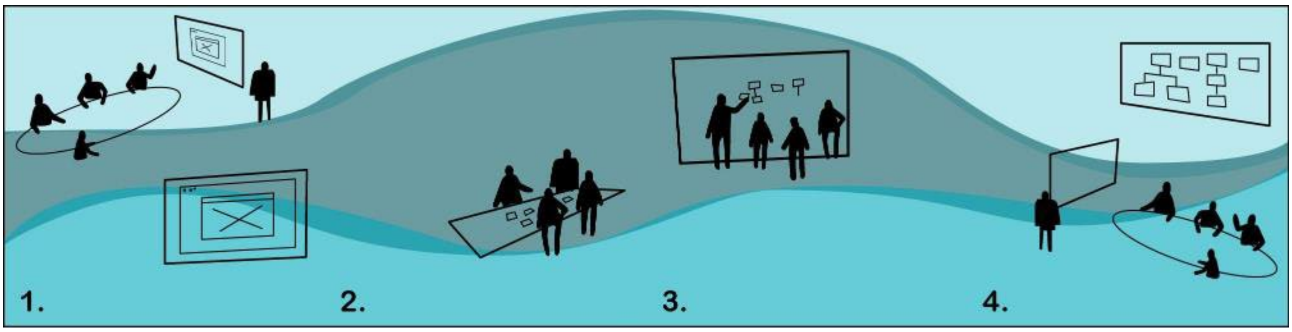


Figure 5: Use case C

1. *Presentation of the brief and the audit carried out beforehand by the design teams on the current website: first brainstorming on the principles of experience that the participants think are the most adapted.*
2. *The imagined functionalities are then materialized collectively in the form of paper "functional bricks".*

3. *These functionalities are then composed in the form of a tree structure, in group, then presented to be annotated by the participants.*
4. *The work done during the workshop is then presented to the workshop participants.*

Being concerned by a trouble: curating the concern

Our comparative analysis highlights three conditions in the emergence of a shared trouble within a prototyping situation (Fig.6): visualizing a situated and dynamic antagonism, considering all the voices of people and using space as a designing background. These conditions inform us about levels of action for curating a concern.

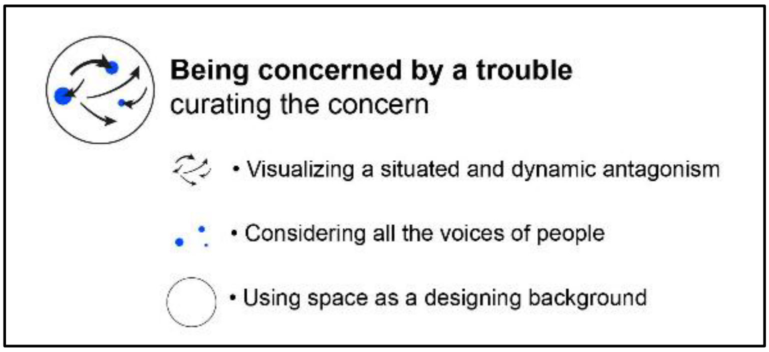


Figure 6: Three conditions for the emergence of a trouble within a prototyping situation (in the form of pictograms).

First of all, it seems essential that a prototyping situation always starts from a commission that makes a project dependent on a field, ready to be explored (Frodon, 2022). Working from existing situations (seen as design materials) allows the formulation of a trouble, more or less experienced by actors, through formats which are sufficiently plastic to maintain a plurality of perceptions around this trouble. Without this situated aspect of prototyping, the trouble cannot be grasped in all its diversity: managing to map this plurality makes the formulation of a trouble visible without being too prescriptive or unequivocal, as it supports a collective formulation of the trouble during all project stages. At the same time, it makes it possible to keep track of the project, to understand which issues need to be discussed at which times and to make visible how the group works dynamically on a trouble.

Then, although the trouble is expressed in a collective way, the prototyping situation should allow each participant, not only designers but all the people involved in the formulation of a trouble (users, clients, etc.) to describe individually the way they perceive it. Thus, the prototyping situation should provide subspaces where personal expression is possible throughout the project (Thoring et al., 2018) making visible all the potential places associated with the trouble. These places expand the scope of the field exploration, allowing the prototyping situation to be situated in different places, each time involving specific formats, with the objective of considering all the voices concerned by the trouble in question. Consequently, it seems important that a preliminary work is done with a panel of actors, representative of the plurality of the trouble in order to pluralize the places where the prototyping situation could occur and the trouble could be formulated.

Finally, to support the collective formulation of a trouble, the situation should consider the possibility of spatializing data involved in this formulation. Space can become a designing background for the trouble (Keller et al., 2006). Forasmuch as the prototyping situation is not situated in a single place, each space should make sense for actors by facilitating a work of composition, hanging, collage and juxtaposition of data. Curating the concern should also consider the explicitation of a valid type of speech: informing, instructing, persuading, criticising. Describing which type is used allows for a better positioning of actors in relation to what is said. The prototyping situation should thus be able to make people aware of the plurality of ways of expressing themselves within and on a project.

Defining a problem: building a public

Our analysis highlights two conditions that contribute to the definition of a problem through a work of investigation within a prototyping situation (Fig.7): labelling a thing and using the space as a parliament. These conditions seem to support the transformation of a group of people (concerned by a trouble) into a public whose objective is to characterize a trouble by a problem.

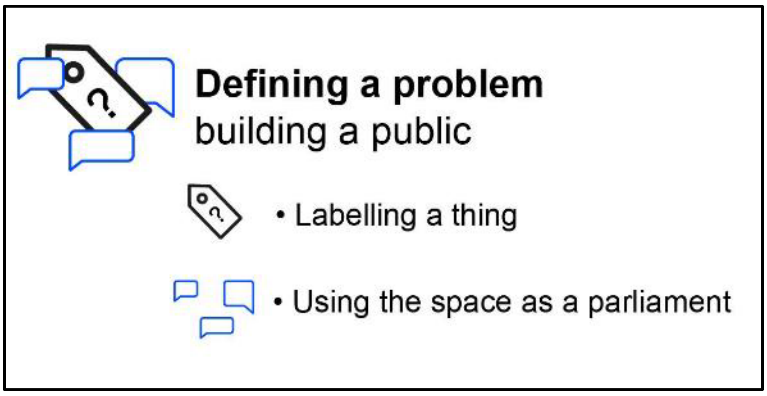


Figure 7: Two conditions for the definition of a problem (by a public) within a prototyping situation (in the form of pictograms).

First, the prototyping situation can be seen as the material translation of a trouble in terms of causes, factors and liabilities (Mollon, 2019): through data collection formats, more or less participative, the goal is to identify which elements allow the group to define the trouble as a problem. Therefore, it seems necessary that these formats make visible, at different places and times, the potentiality of a data to be part of a wicked problem (Rittel & Webber, 1973). Here prototyping is thus considered as a way of labelling a thing or Ding (Latour & Weibel, 2005) into a problem which reveals the invisible forces and political tensions at work in a trouble. To do so, the prototyping situation should support the documentation of all the labellisations of the thing and the definitions of the problem in order to keep track of the many possibilities for a public to justify its existence.

Second, defining a problem within a project requires to take into account the spatial properties of the prototyping situation which allow to discuss around collected data. The space should thus be modular enough to produce different types of physical and discursive confrontation: semicircle, circle, horseshoe, classroom, opposing-bench, etc. (XML, 2016). By diversifying the ways in which speech is materially produced, the work of problematization is fed by the many points of view that these types bring out (Luck, 2010). Space thus becomes a parliament, a place where the definition of a problem is realized. But beyond space, it is also the relationship to time that should be considered. The prototyping situation encourages a total immersion, over short or long periods, from which key moments emerge, helping to develop the problem more precisely.

Being visible: opening new project paths

Finally, the comparative analysis highlights three conditions that shed light on operations involved in the visibility of a project carried out by a design project-team (Fig.8): searching for a common horizon, adapting communication modes, and building the space as an exhibition. Here, the act of prototyping requires us to think the communication's project as a way to design. Therefore, each moment of public presentation, not only at the end of a project, potentially creates new design paths and opens up the scope of the project.

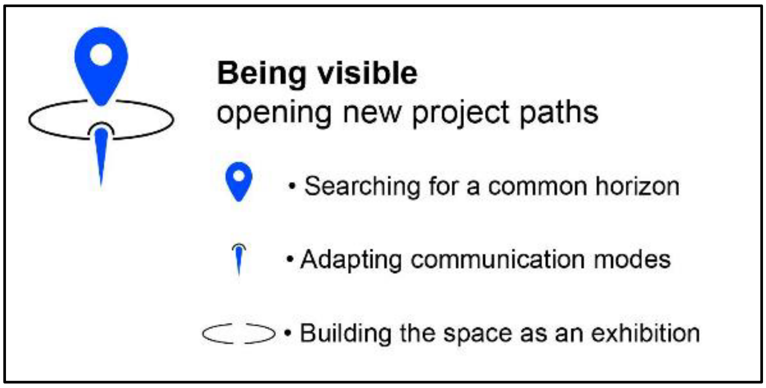


Figure 8: Three conditions for the visibility of an arena within a prototyping situation (in the form of pictograms)

First of all, the communication of a project should be adapted according to audiences in order to potentially involve them in the project and make them feel concerned by the problem (and the trouble) formulated by the team. From this point of view, it seems essential to pluralize the formulations of the problem and identify issues at stake for each audience in order to adjust the discourse as best as possible. Previous conditions we described earlier play a key role here. Therefore, communicating a project is not only a matter of providing information but also generating agency within the audiences to continue building the project.

Thus, seeing communication's project as the potential emergence of agency within an audience makes it possible to extend the scope of project's visibility from its beginning (Ricci, 2022). There is a challenge of adapting the modes of communication according to the situation of communication: the creation of formats informing on the project while allowing audiences to participate is a goal that any situation of prototyping can take into account. Participative design tools of observation and ideation should therefore also facilitate communication of the project and its issues. This goal of mediation is fundamental because it demonstrates the potentiality for communication to sparke a trouble within the audiences and offer new paths of action and reflection to the project.

Finally, the prototyping situation can be seen as an exhibition space (Mabi & Monnoyer-Smith, 2012) where the project is both a communication situation and a design situation (Gentès, 2022). Considering these two sides allows for the arena to make itself visible to other audiences. To do so, the visual identity of the project should be built at the same time as the project as long as it reflects the different perceptions around the trouble. This supposes that the space properties should take into account different types of speech, according to the stakes of communication and the material properties at disposal.

The analysis of three prototyping situations allowed us to identify various conditions for the emergence of an arena. Our goal is to point out how a prototyping situation can be experienced as political, beyond a functional approach. Indeed, if we consider prototyping as a space of deliberation, then the transition from one prototype to another should not be based on the criteria of resolution allowing to reject or validate hypotheses (Vinck et al., 1996). This way of reasoning forgets that each prototype is a world in itself that does not communicate the same issues for the project and for the life experiences it addresses. To consider an MVP (Minimum Viable Product) as the only valid version of a project is to consider design in a linear way. A prototype is therefore not only a static means of translating an idea but also a breaking point in terms of representation which influences the understanding of a project, particularly in a collective design situation. In this way, prototyping makes it possible to grasp different levels of agreement, even partial, on how to build a project (Subrahmanian et al., 2003). This last comment is essential because it considers a prototype as a boundary object whose primary role is to bring together actors from different discourse communities (Krippendorff, 2012). A prototype thus serves here as a deliberation space allowing debate around project's stakes and the most adapted ways to pursue them (Fig. 9).

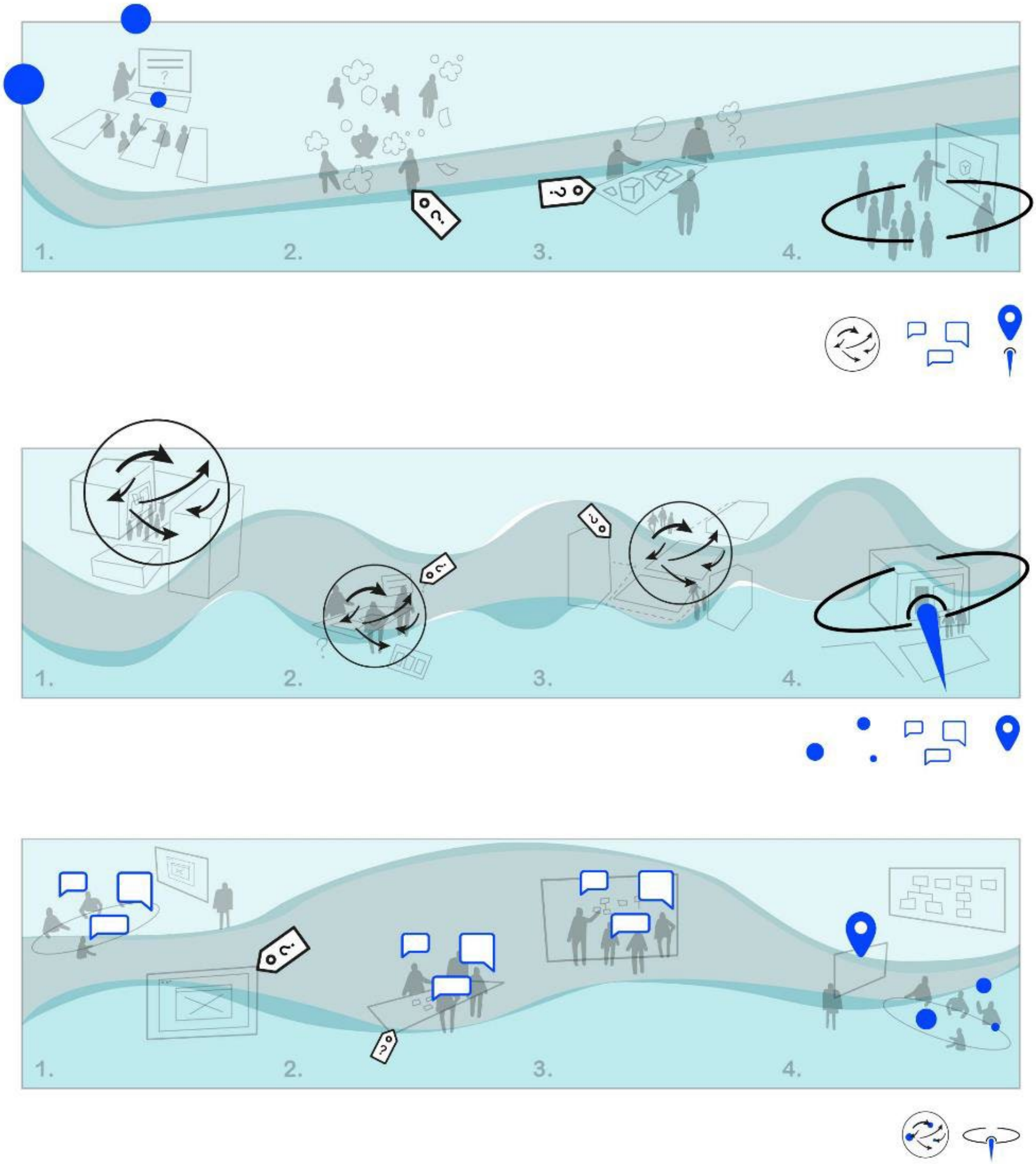


Figure 9: Visualizations of the missing conditions for each of the prototyping situations. Each missing condition is located at the bottom right of the strip.

For example, on one hand, situation A allows a personal formulation of a trouble through a question (considering all the voices of people). On the other hand, the collective formulation of the trouble is less present because the properties of the space do not allow the visibility of the many points of view around the trouble (visualizing a situated and dynamic antagonism). The work of problematization, in spite of imposed formats of exploration (labelling a thing) could not be completed because the project exists outside a concrete commission and a real field of exploration. Therefore, the project is limited to the space of the class. By working the prototyping situation as a communication space (using space as a designing background), the situation could have better situated each of the project group in a real field of exploration with stakeholders while allowing for a collective construction of a problem (searching for a common horizon).

On the contrary, situation B put the emergence of collective trouble at the heart of the project. The personal experience of the trouble is captured through various participative design tools (labelling a thing). This approach also allows them to communicate differently about the project and to engage new audiences but not collectively (adapting communication modes). It also shows a light participation from actors because the personal experience of the trouble is collected without being followed by a deep exploration of it (considering all the voices of people). By designing tools that facilitate the sharing of the trouble more profoundly, the work problematization would have allowed actors to discuss more (using the space as a parliament) and would have opened the project to more appropriation.

Finally, situation C engages stakeholders with an already formulated trouble. Therefore, space becomes only a place for building a problem (using the space as a parliament) but in a collective way (labelling a thing). By focusing more on formulating the trouble (visualizing a situated and dynamic antagonism), the prototyping situation would have gained in plurality, allowing to reinforce the commitment of actors (building the space as an exhibition). Indeed, even if the prototyping situation has brought out new subjects of discussion during the restitution, this does not mean that the problematization work has allowed us to explore all dimensions of the trouble (considering all the voices of people and searching for a common horizon).

Our comparative analysis between various elements shows how these conditions could be brought out of functional approaches of prototyping. In this respect, prototyping situations we have analyzed could be seen as a political experience but it seems that their conditions do not vary enough to really bring out arenas. Envisioning prototyping as a situation was the first step of a consideration about the conditions needed to make a political experience happen. It could be interesting to use the framework sketched in this paper to analyze more prototyping situations but also to create new ones. Thus we could vary the many different forms of arenas allowed by prototyping and pursue the study of the political in the ordinary practices of design.

Informing Design Practices through the Political

This paper can be considered as a first step of a more extensive research about the way a political experience of design could occur within design practices. It provides tools for designers and design practitioners to think about prototyping as a situation, and notably a political one. The graphic work we designed has two interests. On the one hand, it gives an analytical framework for any prototyping situation allowing designers to understand moments of emergence (or not) of a political experience. On the other hand, it gives a tool for setting up a prototyping situation, based on political experience conditions, and thus leaves the possibility for an arena to emerge.

More generally, what we are trying to emphasize is the reflexive dimension of design practice that pushes the practitioner to think, beyond the emergence of ideas, about the material conditions of the emergence of political arguments that can forge and build a political arena.

Therefore, this research is trying to explore ways of making the practitioner feel concerned (producing matter of concern from the designer and the participants), by being a complete actor in the project for which he or she is responsible. In this sense, we come close to some activist practices in design (Bieling, 2019), in which the personal interest of the project for the designer is a corollary to its application. This way we question the working environments of designers and the habits that are forged there over time: from the moment that a designer fixes his or her practices in a specific environment, how can he or she guarantee a political experience of this environment? Or, on the contrary, when the designer is not aware of the classification systems of a situation, how can he or she work on the conditions for questioning these systems? And, on a more general level: iin what ways designers could embody the political dimension of their practice knowing that they participate in a material culture of which we are aware of its limits today?

This article brought a series of questions we could explore by engaging a more extensive research on how prototyping could be the most adapted situation to experience the political in design because it brings together human and non-human actors into a co-design process where debate is necessarily present. In his compositionist manifesto, Bruno Latour calls for thinking politics as the progressive composition of a common world. Pluralism should be the primary material from which it becomes possible to come together, to deliberate: "if we put aside what separates us, there is nothing left for us to put in common" (Latour, 2022, p. 14).

Thinking from the point of view of pluralism means accepting that the political can emerge as much from parliaments as from: "Scientific laboratories, technical institutions, marketplaces, churches and temples, financial trading rooms, Internet forums" (Latour, 2022, p. 21). All of these places show different material properties inducing different ways of speaking, ways of coming together, of raising a concern, of deliberating, of designing.

References

Auger, J. (2012). Why Robot? Speculative design, the domestication of technology and the considered future.

Beaubois, V. (2015). Ethnographies du design : Vers une diagrammatisation de la conception. Techniques & culture*, 64, 48-63. https://doi.org/10.4000/tc.7558*

Cefaï, D. (2016). Publics, problèmes publics, arènes publiques… : Que nous apprend le pragmatisme ? Questions de communication*, 30, 25-64. https://doi.org/10.4000/questionsdecommunication.10704*

DiSalvo, C. (2015). Adversarial design*. The MIT Press.*

Dunne, A., & Raby, F. (2007). Critical Design FAQ. Dunne & Raby*. http://dunneandraby.co.uk/content/bydandr/13/0*

Dunne, A., & Raby, F. (2013). Speculative everything : Design, fiction, and social dreaming*. The MIT Press.*

Frodon, J.-M. (2022). La commande comme dispositif actif, les commandes comme réalités multiples. In F. Aït-Touati, J.-M. Frodon, B. Latour, & D. Ricci (Éds.), Puissances de l'enquête : L'École des Arts politiques*. Les Liens qui libèrent.* https://hal.archives-

ouvertes.fr/hal-03776222

Gaver, W., Krogh, P., Boucher, A., & Chatting, D. (2022). Emergence as a Feature of Practice-based Design Research. 517-526. https://doi.org/10.1145/3532106.3533524

Gentès, A. (2022). Pour une théorie " média-centrée " du design. Approches Théoriques en Information-Communication (ATIC)*, 4(1), 51-71. https://doi.org/10.3917/atic.004.0051*

Haraway, D. J. (2016). Staying with the trouble : Making kin in the Chthulucene*. Duke University Press.*

Keller, A., Pasman, G., & Stappers, P. J. (2006). Collections designers keep : Collecting visual material for inspiration and reference. Codesign*, 2, 17-33. https://doi.org/10.1080/15710880600571123*

Keshavarz, M. (2016). An Inquiry into Passports, Camps and Borders *[Thèse de doctorat, Malmö University].* https://www.diva-portal.org/smash/get/diva2:1404323/FULLTEXT01.pdf

Koskinen, I. (2010). Two Solitudes : Design as an Approach to Media Studies. Nordicom Review Vol. 27(2), Nov. 2006, pp. 35-47.

Krippendorff, K. (2012). Le discours et la matérialité de ses artefacts (A. Bahroun, Trad.). Communication & langages*, 173(3), 17-42. Cairn.info. https://doi.org/10.4074/S0336150012013026*

Latour, B. (2022). Pour une école des arts politiques, Manifeste Compositionniste. In F. Aït-Touati, J.-M. Frodon, B. Latour, & D. Ricci (Éds.), Puissances de l'enquête : L'École des Arts politiques*. Les Liens qui libèrent. https://hal.archives-ouvertes.fr/hal-03776222*

Latour, B., & Weibel, P. (Éds.). (2005). Making things public : Atmospheres of democracy*. MIT Press ; ZKM/Center for Art and Media in Karlsruhe.*

Luck, R. (2010). Using objects to coordinate design activity in interaction. Construction Management and Economics*, 28(6), Art. 6.*

Mabi, C., & Monnoyer-Smith, L. (2012). Les arènes du débat public. Comprendre les logiques de mobilisation des différentes arènes de discussion par les acteurs d'un débat public. Communiquer dans un monde de normes. L'information et la communication dans les enjeux contemporains de la " mondialisation "., 281. https://hal.univ-lille.fr/hal-00826084

Mollon, M. (2016) Dissensus : For a situated critical design, out of museums*.*

Mollon, M. (2019). Design pour débattre : Comment créer des artefacts dissonants, et leurs situations de communication, afin d'ouvrir des espaces de contestation mutuelle (agonisme) et d'expression des voix marginales (dissensus) *[Phdthesis, Université Paris sciences et lettres]. https://theses.hal.science/tel-03120398*

Mouffe, C. (1993). The return of the political*. Verso.*

Mouffe, C. (2005). On the political*. Routledge.*

Ricci, D. (2022). Des exercices. In F. Aït-Touati, J.-M. Frodon, B. Latour, & D. Ricci (Éds.), Puissances de l'enquête : L'École des Arts politiques*. Les Liens qui libèrent. https://hal.archives-ouvertes.fr/hal-03776222*

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. Policy

Sciences*, 4(2), 155-169. https://doi.org/10.1007/BF01405730*

Schön, D. A. (1983). The reflective practitioner : How professionals think in action*. Basic Books.*

Sengers, P., Boehner, K., David, S., & Kaye, J. " Jofish ". (2005). Reflective Design*. Proceedings of the 4th Decennial Conference on Critical Computing: Between Sense and Sensibility, 49-58. https://doi.org/10.1145/1094562.1094569*

Subrahmanian, E., Monarch, I., Konda, S., Granger, H., Milliken, R., Westerberg, A., & Then-dim group. (2003). Boundary Objects and Prototypes at the Interfaces of Engineering Design. Computer Supported Cooperative Work (CSCW)*, 12(2), 185-203. https://doi.org/10.1023/A:1023976111188*

Thoring, K., Desmet, P., & Badke-Schaub, P. (2018). Creative environments for design education and practice : A typology of creative spaces. Design Studies*, 56, 54-83. https://doi.org/10.1016/j.destud.2018.02.001*

Vinck, D., Jeantet, A., & Laureillard, P. (1996). Objects and Other Intermediaries in the Sociotechnical Process of Product Design : An exploratory approach. In V. (Dominique) PERRIN (Jacques) (Éd.), The role of design in the shaping of technology *(p. 297-320). Directorate General Science, R&D. https://shs.hal.science/halshs-00273425*

XML. (2016). Parliament*. XML.*

Yu, F., Pasinelli, M., & Brem, A. (2018). Prototyping in theory and in practice : A study of the similarities and differences between engineers and designers. Creativity and Innovation Management*, 27(2), 121-132. https://doi.org/10.1111/caim.12242*

Rose Dumesny

Rose Dumesny, Phd in Information and Communication Science with a specialization in Design. Trained in product design at ENSAAMA-Olivier de Serres, she works as a researcher and experience designer on the links between digital and tangible devices. She defended her thesis in 2019 on mediation through design of complex systems, such as data or AI. The projects she is developing focus on understanding the impact of AI on new services or on design professions in order to develop methodologies to adapt to it.

Dorian Reunkrilerk

PhD in Design sciences and Information-Communication sciences and designer (specialized in service and graphic design). He worked for 4 years for museums and design events in curating and cultural mediation.Through his design practice, the research works he conducts explore modes of mediation between design cultures within organizations from the point of view of objects and their media properties. He’s also a research fellow at the Panthéon-Sorbonne University (in the “Design, Arts, Medias” research group of the ACTE Institute) and at Strate, school of design (in the Strate Research group).

Oxymoron in Prototyping Digital Artifacts: Reviews of Digitalised Product-Service System (DPSS) Development Projects of Global Tech Companies

Hyunwook Hwangbo, Design, Business & Technology Management, Faculty of Architecture and Planning, Thammasat University, Thailand

Abstract

Prototyping is one of the vital attributes of establishing a design-thinking organisation. This study suggests it also implies its oxymorons as an organisational material practice when it comes to digitalised product-service system (DPSS) development practice. DPSS development involves digital artefact design. This however requires a new organisational approach to prototyping. Designing a digital artefact is concerned with digital materiality - a combination of heterogeneous digitised materials: tangible materials (products and network systems) with intangible ones (service and contents), accomplished in a generative design approach. But it also presents new organisational challenges on increasing unknown factors emerging from the heterogeneous and generative design practices, calling for dedicated experiential learning practices through organisational prototyping. Qualitative case studies of three tech companies sharing common design philosophies found key organisational barriers to establishing a prototyping culture in association with DPSS development projects. It revealed that prototyping processes and the outcomes can be purposively manipulated for an organisation's exploitative purposes. As an organisation's social material practice, increasing unknown factors associated with digital artefact design engage with characterising an organisation's concerns on the unknown. These are likely reflected in organisational prototyping. In an organisation's design process, its conventional assumptions coupled with dominant analogies, superiors' high power desirability and its coercive bureaucratic features reflected in prototyping processes can implicitly lead its prototyping to its exploitative purpose instead of experiential and exploratory purposes. This study presents empirical evidence that prototyping as an organisation's social material practice connotes its oxymoron.

Prototyping culture, generative capacity, design thinking organisation, digitalised product-service system(DPSS), sociomateriality

In a product and service development process, an organisation's approach to prototyping reflects its culture in association with professional culture dominating in design practice (e.g. engineering) and ways of communication between members that engage with the complex practices – e.g. decision-making between powers and design communities etc. (Schrage, 1996; Camburn, et al., 2017). Such prototyping enabling organisation can be denoted as prototyping culture (Camburn, et al., 2017; Schrage, 1996). Likewise prototyping in organizational contexts has been studied and empirically researched in a wide range of design and management-relating studies from prototyping practice: organisational factors that contribute to design fixation in prototyping (Youmans, 2011) to meaning of prototyping as material practices in organisation: prototyping culture is a key source of design thinking organisation which emphasizes collaborative, participatory and iterative problem-solving approaches (Elsbach & Stigliani, 2018; Camburn, et al., 2017; Bogers & Horst, 2013), prototyping can be performed differently depending on characteristics of bureaucratic systems an organisation adopts (e.g. engaging vs. coerciveness in organisational formalisation) (Adler & Borys, 1996; Adler & Winograd, 1992), prototyping a complex technology system is an embodiment of social material practices of an organisation and the technology prototypes as the configuration of its socio-material artefacts (e.g. hardware, software and relevant work practice) (Suchman, et al., 2002; also Orlikowski & Scott, 2008).

Within the context, applications of service-dominant (S-D) logic in the field of design studies and blurring boundary between product and service call for new understandings of product and service design, namely, product-service system (PSS) (Vargo & Lusch, 2017; Sangiorgi & Junginger, 2015). But the emergence of PSS also requires a new organisational approach to designing and prototyping (Camburn, et al., 2017). PSS refers to a bundle of physical products (the offerings and benefits delivered from tangible material properties to customers) and intangible services (the offerings mostly provided in the form of the intangible). From an economic perspective, products and services are closely related to one another as information systems and technologies advance. Most service offerings are provided in conjunction with such physical products and vice versa (Grönroos, 2006; Ulrich & Eppinger, 2016): for example, mobile communication systems delivered by hardware handsets (products) and mobile network (service), healthcare offerings delivered by a combination of medical devices (products) and medical diagnosis and advice (service) and so on.

In line with this, the concept of PSS that enables digital services and products has been introduced, called a digitalised product-service system (DPSS): such intangible offerings (e.g. digital network-based services and contents) delivered and consumed via digitised hardware (Lenkenhoff; et al, 2018). Broadly speaking, DPSS is involved in digital artefacts, characterized as ‘digital materiality’. That is a combination of heterogenous kinds of materials between software (contents and service) and hardware (network and device) ‘heterogeneity’ (Yoo, 2012; Nylén & Holmström, 2015). Offerings, functions and features of such digital artefacts – i.e. DPSS- can be continuously changed, revised and updated by which diverse ranges of co-designers (e.g. users, platform complements etc.) openly engage in editing, reprogramming and/or updating digital data encoded in the system. In doing so, the meanings of such digital artefacts can be continuously rejuvenated with indefinite possibilities, namely, generativity (Yoo, 2012; Nylén & Holmström, 2015).

Yet, scholarly discussion on prototyping for digitized PSS (DPSS) is still in its infancy (Camburn, et al., 2017; Ruvald, et al., 2020). This paper is therefore aimed to bring a new understanding of interwoven relations between organizational material practices reflected in prototyping digitalised PSS (DPSS). This paper is organised in accordance with the research questions guiding this research. The following literature review will present theoretical background to answer the question of *i) how prototyping for digitalized PSS (DPSS) as a digital artefact might have to be approached*. Following that, findings from from the multiple case studies will answer the question of *ii) what organizational components might be concerned with the prototyping processes in actual organizational settings*. Based on the insights gained from the case studies, it is to be discussed *iii) how those organisational* *factors might affect the prototyping as an organisational material practice (i.e. DPSS development as digital artefact design).*

The theoretical framework

Prototyping as an organisational material practice

New product development is a representative organisational practice that mirrors an organisation's series of managerial actions for complex problem-solving related to its material practice - e.g. product and/or service designs (Junginger, 2008; Ulrich, 2016). In product (or service) development, prototyping plays a vital role as a manifestation of the organisational practice. Prototype refers to an approximated artefact that can show a feature (or multiple features) of a product to be designed - e.g. concept sketches, mathematical models, simulations, test components, a fully functional production version of a product etc. Prototyping as an organisational practice is not only limitedly aimed at hardware product development, but also involved with service, or system design (Ulrich, 2016; Camburn, et al., 2017). It contributes to evaluating and testing whether at least one attribute of a product to be developed would be able to work, in terms of, for example, looks & feels, technical features & function or/and both (Ulrich & Eppinger, 2016; Camburn, et al., 2017). In doing so, it presents analytical evidence to demonstrate, for example, such user desirability (e.g. user need testing), business viability (e.g. market potential) or/and technical feasibility (e.g. computer modelling embedding a dynamic simulation model) in a visual and/or mathematical manner (Brown & Wyatt, 2010; Ulrich, 2016). Then it enhances reliability in such complex technical and engineering products to be developed, so as to measure and reduce anticipated risk: (Ulrich & Eppinger, 2016; Camburn, et al., 2017). As an organisational material practice mirroring one's complex design practice, prototyping has the following functions.

Firstly, it contributes to organisational learning in accomplishing complex design practices (Camburn, et al., 2017; Ulrich, 2016), through tacit and explicit engagement with organisational learning between designers (Nonaka, 1994). Then it contributes to complex design problem-solving in design practices (Camburn, et al., 2017; Ulrich, 2016). Secondly, it is a 'communication' tool and plays a role as a key channel between diverse stakeholder groups, which helps them to interact and reach decision-making (e.g. top management, vendors, partners, extended team, vendors, customers, investors etc.) (Ulrich, 2016). It acts in organizational information processing for knowledge creation so as to contribute to complex design problem-solving. With the use of a tangible prototyping outcome that has a certain level of fidelity, the interactive communications between design stakeholder groups contribute to promoting the exploration and ideation process. Then it is to elaborate a new design concept or/and draw noble design solutions throughout the iterative prototyping process (Camburn, et al., 2017; Ulrich, 2016). Yet, if such communication for prototyping involves too long feedback processes in design-decision making process with senior decision makers or/and top management, the prototyping process can be at risk to lead to conventional communication within dominant organisational logics and analogies (Camburn, et al., 2017), which results in 'design fixation' (Crilly, 2015; Schrage, 1996). In association with all those, prototyping plays a role as a 'medium' between product development relevant groups for rational-design decision making– e.g. the marketing, design and manufacturing:

evaluating and testing technical feasibility in new product development, followed by constant refinement (Camburn, et al., 2017) and integrating process at a product system level (Ulrich, 2016). Lastly, prototyping is characterised as a 'milestone' in the process of demonstrating whether such a complex technical product would be able to achieve the desired level of functionality (Ulrich, 2016) and that usability etc. (Camburn, et al., 2017).

However, despite the increasing complexity of digitalised products and services - e.g. DPSS, prototyping has been discussed mostly in hardware-relevant product design, not likely on the intangible (Camburn, et al., 2017). Nor have those been approached from comprehensive organisational design perspectives, considering organisational components -e.g. structure or culture (Elsbach & Stigliani, 2018).

Generative capacity and prototyping culture in a digital age

With reviews of such key features of prototyping in organisational design practice, Schrage (2006) introduced the concept of 'prototyping culture'; a creative and innovative organisational culture which values exploratory and agile design approaches, so that enable such iterative and process-oriented prototyping processes.

The notion has been echoed by many design and management relevant organisation studies, for example, 'design thinking organisation' (Elsbach & Stigliani, 2018; Andrew & Sirkin, 2006). That is extended to account for key characteristics of an organisation that builds digital artefacts by highlighting the generative capacity of an organisation: the capacity of a group (e.g. an organisation) or human-made artefact to (re)produce or (re)generate something new by rejuvenating it with indefinite possibilities (Avital and Te'eni, 2009; Ven, et al., 2013; Yoo, 2012). It is inspired by multiple architectural design projects run by architect Frank O' Gehry's office. Despite such huge complexity of those projects, in which diverse ranges of stakeholder groups in architecture, construction person, engineering sides etc. engage (Yoo, et al., 2006; Boland, et al., 2007), unique forms of his architectural design have been successfully realised by the office's a series of prototyping processes (e.g. from Gehry's conceptual sketching into the 3D rendering by using computer software etc.) to refine concepts and forms (Boland & Collopy, 2004; Elsbach & Stigliani, 2018). Then, the design organisation (i.e. Gehry's design studio) shows the following attributes that can enable it to perform its generative capacity to accomplish such complex architectural design projects heterogeneous design stakeholders involve.

First, the organisational environment is open–ended (Yoo, et al., 2006; Avital and Te'eni, 2009). That enables stakeholder groups to engage in generative form giving: e.g. searching for alternative design solutions and applying more design options followed by visualising and simulating various unprecedented events for testing and examining abstraction (Avital and Te'eni, 2009). Secondly, it shows an adaptive feature (Yoo, et al., 2006). That allows an organisation to relate to a dynamic, changing environment, which in turn diverse designers can be enabled to engage in their design tasks autonomously from each discipline's respective perspective (Avital & Te'Eni, 2009). Lastly, the organisation with enhanced generative capacity values autonomous and self-guided design problem-solving processes between individual designers. Then it can encourage design stakeholders from diverse disciplinary groups to openly engage in co-design activities. It enables them to suggest the best temporal solutions drawn from each discipline's best practices (temporality), with little constraint from conventional assumptions (Yoo, et al., 2006).

Challenges in DPSS development as digital artefact design: increasing unknown factors

Establishing a prototyping culture is challenging because of increasing unknown factors from managing complex digital artefact designs. Digital physical product development practice explicates such challenges in association with managing the unknown in digital artefact design practice (Table 1). DPSS is accomplished by Digital-physical product development practice: the organisational design practice applied in the transformation of previous non-digital products into digital products and services by adding digital technology (Hendler, 2019; Svahn & Henfridsson, 2012). But it connotes the following modalities that cause such unknown factors in the design practice: ***diversity, complexity, uncertainty,*** *and* ***interdependency*** (Table 1).

Firstly, it is concerned with a high degree of diversity. Digital-physical product and service development processes require considering information and knowledge from multiple heterogeneous domains (software and hardware) (Hendler, 2019). The use of widely distributed information and innovation networks promotes diverse co-designers engagement in such generative design practices. But increasing heterogeneity in the knowledge creation domain - e.g. hardware and software - should be dealt with to accomplish a design project.

Secondly, such heterogeneity-driven design practice causes increasing 'complexity' in the design practice. Designers who experience only their own discipline or relevant knowledge domains are likely to have difficulty understanding new design problems occurring in heterogeneous components (Hendler, 2019).

Thirdly, such increasing complexity in the design practice presents concerns about increasing the level of uncertainty in the design practice (Hendler, 2019). A design group that has rarely experienced such heterogeneous design components requires more time and resources to evaluate the information collected in order to generate new knowledge for problem-solving (Milliken, 1987).

Lastly, considering all the above, the design practice is concerned with a high degree of interdependence in accomplishing the design tasks. Functioning a digital artefact as a whole is a result of an interdependent operation between all relevant hardware and software components which contribute to digital product architecture (Yoo, et al., 2010) and consequently digital artefact as a whole - e.g. digital product, service and product-service system, platform. It is important codesigners engaging in the design practice consider how those components would work, interdependently

Above all indicate that DPSS development demands a dedicated organisational approach to prototyping in order to cope with such increasingly unknown factors in the design practice. But it also implies to underline supportive organisational culture that can enhance its generative capacity so as to promote dedicated prototyping in real organisational contexts (Ven, et al., 2013; Boland & Collopy, 2004).

Category	Definition & attributes
Diversity	A status that indicates that a variety of works, expertise and disciplines have to be adopted in order to acquire the range of competencies needed to perform an innovation process
Complexity	Status that people are hard to understand and analyze their work due to incrementally increasing new information from heterogeneous and volatile organizational environment
Uncertainty	A status indicating that people are incapable of predicting the future precisely, due to a lack of information about it
Interdependency	A status that indicates the extent to which diverse disciplines and professionals collaboratively rely on, carrying out a complex innovation process

Table 1. Definitions of key factors considered in digital artefact design practices (adapted from Boer & During, 2001)

Qualitative research approach

Case study: synthesis by explanation approach

In the empirical research a case study approach was used to offer exploratory insights (Yin 2009), employing an approach of 'synthesis by explanation' - seeking discernable patterns from documentary sources that contain empirical qualitative data to supplement the author's interpretation: e.g. qualitative case studies, interview quotes etc. (Rousseau, et al, 2008). *This is performed by using* mixed qualitative methods techniques: incorporating the analysis of original interview transcripts (over 76,000 words transcribed from recording the 23 in-depth expert interviews done between August 2013 to September 2014) into that of a range of multiple documentary sources, aimed at construct validity between those qualitative datasets (e.g. books and academic journals which contain empirical data, interview quotes, case studies etc. on those companies) (Bowen, 2009; O'Reilly & Kiyimba, 2015; Yin, 2009).

A total of three cases have been selected to analyze: Sony, Samsung and Theranos which have influenced one another in terms of design philosophy and design strategy: Sony's design philosophy inspired Steve Jobs' Apple product design (Isaacson, 2011) and Samsung's design philosophy (Cain, 2020); Also, Apple's design philosophy and strategy inspired Samsung's (Cain, 2020) and entrepreneurship of Theranos as well as her company's product and service design (Carreyrou, 2018). In common, those provide DPSS types of offerings: Sony and Samsung (diverse ranges of their digital service and contents via their hardware handsets) and Theranos: healthcare service (diagnosis & advice) via its medical devices.

The collected qualitative data were analyzed in a thematic analysis approach (Braun & Clarke, 2006). Initially, the interview transcripts regarding Samsung & Sony cases generated 472 reference codes. These were regrouped into the eight subcategories related to major causes of organisational concerns which may impact prototyping. From the subcategories, the four key main themes were drawn in relation to key organisational characteristics that may be caused by those organisational factors indicated in the sub-categories (figure 1).

The key themes were used for the initial analysis of the two cases (Sony & Samsung), and then to be recounted the case, Theranos with the review of a range of documentary data sources, aimed at enhancing triangulation between the qualitative datasets and construct validity between the cases (Yin 2009).

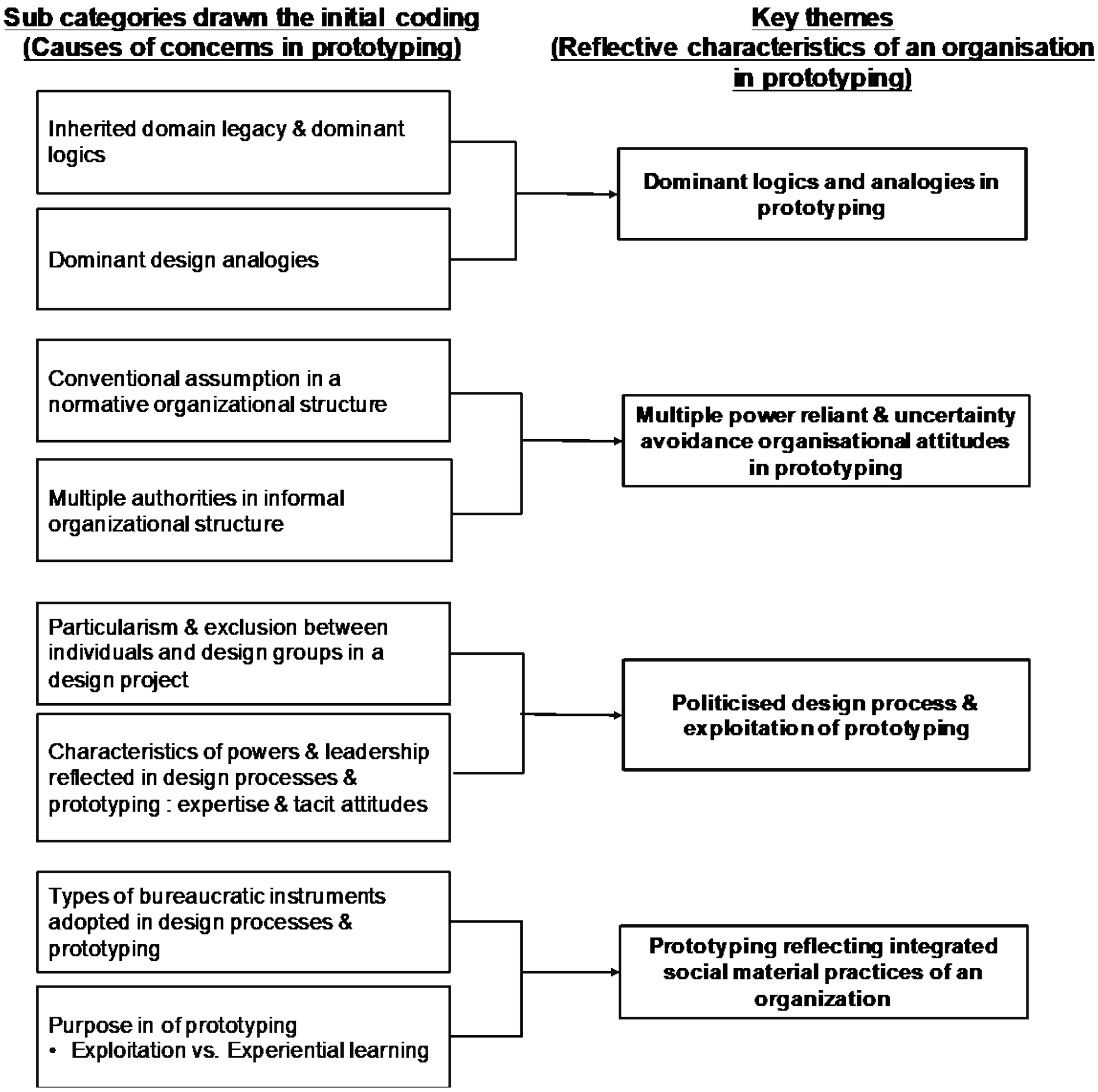


Figure 1. The coding structure & main themes

Findings

Sony: peripheral prototyping

As the digital age began, Sony businesses have been faced with critical challenges from their global rivals, Samsung and Apple (Chang, 2009). It led to the step-down of Ryoji Chubachi, the company's CEO in April of 2009, as a result of being blamed for the defeat of Sony's electronics division in competition with those two global rivals, during his reign. In February 2014, due to poor sales, Sony sold off its VAIO computer division to Japan Industrial Partners (JIP) for 50 billion yen to focus on its mobile business (Smith, 2014).

In 2017, its mobile (which had operated as Sony Ericsson Mobile Communications until 2012) global market share dropped to less than one percent of the global market (Sunnebo, 2017). On April 1, 2021, Sony Mobile division alongside its electronics businesses vanished by being integrated into one company called Sony Corporation.

Dominant hardware-oriented analogies

The enduring hardware domain of Sony contributed to fixating a strategic design approach on their existing dominant logic used for hardware product development, as concerned about a range of explicit considerations on existing resources utilized in hardware manufacturing in a marginal economic sense (e.g. efficient production with minimized costs, and maximized profitability). But it consequently prevents the design group from adapting it to strategic business model innovation to utilize heterogeneous and generative design practice needed for DPSS.

"It's something to do with cost things within the hardware-based company. Because tooling is obviously very expensive. They are more expensive than the infrastructure related to service stuff. […] So when a project starts off, for example, I have to go and say, "Who is going to pay for my time?" The budget holder will be engineering. Always engineering because it is concerned with cost." (19)

Multiple powers reliant design-decision making processes

Back in 2013 and 2014, Sony still showed a conventional organisational form that relies on a widely divisionalised organisational structure; aimed at traditional manufacturing practices and the linear and hierarchical manufacturing process (also Chang, 2008). Its design process rather relies on obscure decisions made by multi-layered power structures. Accordingly, conventional Asian organisational culture characterised by collectivism (based on in-group respect) and power-centric organisational attitudes (hierarchy between superiors and fellow members is an existential inequality) (Chang, 2009; Hofstede, et al., 2010; Cain, 2020) pervaded in design-decision making processes. Those hinder creating an open-ended, autonomous and self-adaptive organisational mood to cope with such complex and uncertain design practices, as remarked following:

“In Sony, teams are created based on understanding and mutual respect. So I had been a project planner. I was working with them for three or four years. We really work hard together. We respect each other. So then whenever we had a different project or even none of my area, we always say "I would like you to ask 'Ra- San". Because he trusted me. Because he can assure his boss. Then the boss authorizes me. It is like sub-hierarchy […] it's a weird mechanism. It's not like army like structure where orders take place like a machine, but rather political and group-oriented; everything under one head in one house.” (19)

"There was a product that we wanted some years ago, called Xperia Play. But the device launching got delayed. The project was kind of zombie, die and come back again. It's because the top management from all divisions had to reach an agreement such as; who does what? who does this part for software? Who would own the product part? Who would be responsible for launching? and so forth." (23)

Lack of expertise in the power structure

The such organisational mood is also attributed to a leader's characteristics shown in key design-decision-making processes, such as lack of professional and educational backgrounds on digital artefact designs, which may cause a high level of uncertainty avoidance attitudes across the organisation as such complexity increases. It was involved not only with middle-level management – e.g. mostly hardware engineers who lack software domains but also the top management as evidenced in the case of former CEO, Howard Stringer who served until 1 February 2012.

"Their approach to software is also hardware-oriented. The owner of the project, the general manager is the hardware owner. Now the software general manager reports to the hardware general manager." (19)

"Our CEO didn't have a product-related background but has media relevant background. Howard Stringer reigned for the company but he didn't understand product as much as media. For him, the strategy was about selling product by utilizing media. So he didn't really track too much the product development cycles, nor focused on product itself." (23)

Absence of prototyping process

Such organisational attributes to failure to establish a generative organisation for DPSS were manifested in the absence of a prototyping process while digital product and service development processes were undertaken. Instead, design projects had sporadically taken place in a reductive manner, upon request by such organisations without a long-term strategic roadmap and exploratory, as remarked following.

"Sony didn't have the prototype part in the design division but rather a small one consisting of one or two people. They are nothing really. […] Sony makes TVs. Now Google TV comes out. Sony was panicked then. So, it makes a partnership with Google. And they would say "We are going to make a partnership secretly with such scalable companies in three years. Then we are finding our own system." (19)

Samsung: coercively coordinated design process

Since Samsung Electronics launched its business in January 1969 as an OEM maker of a range of hardware electronic products for a Japanese electronics maker (Panasonic), its fast-follower strategy has driven mass production of its hardware product lines (Chang, 2009) and it contributes to achieving its status as the world top-ranked mobile handset maker with its original brand, by overcoming its handicap as an OEM maker. Despite that, as digital innovation competition began its design strategies and creative capacity associated with digital product and service designs have been in question (Wilson, 2015; Cain, 2020), as evidenced by multiple incidents in the company involves. From 2011 to 2018 the company's design of its 13 flagship Galaxy S lines has been involved with copycat issues with Apple's iPhone and iPad due to the similar look and feel of the devices and the software designs used (e.g. bounce-back response and the tap-and-zoom gesture): in the US, the case has been eventually closed in 2018 with the final verdict of the U.S. District Judge in San Jose, California; Samsung has to pay $539 million for its fine for the infringement of Apple's design (Kastrenakes, 2018). In 2016, its Galaxy Note 7 flagship product has been involved with the issue of technical design failure: overheating and/or exploding issues throughout the overcapacity of the battery built into the device, which results in banning the possession of the device from all US air flights due to the possible risk of accidental fires (Cain, 2020).

Dominant hardware-oriented analogies

Back in 2013 and 2014, Samsung design groups were broadly governed by existing dominant logic rooted in its hardware domain which consequently presented multiple challenges to its business model innovation and changes of design strategies towards holistic DPSS (Chesbrough, 2003; Nagaraj, et al., 2020), as described as follows:

"Our designers often say 'Our scope is only up to here because we are a manufacturer.' They said this company is aimed at manufacturing for mass production […] there are several proposals delivered by a product planning team or the relevant departments. The drafts tend to include specifications and details for the proposals. But engineers' inquiries tend to be considered leading to the acceptance (of the proposal) without further assessment because of their mathematical evidence, whereas designers' ones are unlikely. Because there is no rigorous design initiative process led by designer groups." (21)

The hierarchical power structure and politicized design processes

Samsung also suffered hierarchical design- decision-making processes relying on multiple power structures. But interviewees reported more uniqueness in association with Korean organizational culture, concerned with seniority, rank, and kinship, as follows:

"Hierarchy is very important in my current company. I found that Korean colleges in Seoul are unlikely to speak up or show their opinions if their ideas are different from their managers. Following the order in the company is routine." (15)

"I strongly feel like I am in the Korean army service culture, seriously. Although we are a design team if seniors in management parts ask to change a draft and say that is wrong. Then, design idea must be changed. If superiors think it is wrong, it is wrong without reasons" (21)

Such a unique organisational environment fosters a politicised organisational atmosphere. Particularism and exclusion between design units in product development pervaded, presenting territorial conflicts between those sub-design units and/or authorities in design-decision-making. Then, strategic decisions were shown to be made by following a status quo's political interests, instead of professional ones, as remarked by the following.

"A design project must be carried out by dedicated collaborations between diverse design and non-design groups from software, hardware, marketing, product planning teams etc. However, I often found that a new project requiring extra work to another team or those groups are likely to be less considered or hesitant implicitly." (2)

"How to treat superiors is very important in the Korean company; quick revision of a draft and readily response to their inquiries are all related to it. By doing so, those fellow designers can be acknowledged by their superiors and gain significant kinships with those superiors […] in this mobile division, most design ideas tend to be confirmed and decided by the head of the division, CEO, instead of the design group's one. It means that such good relationships with

the CEO are vital in proceeding with a design project." (21)

Formalized prototyping process

Within that organisational environment, genuine prototyping is unlikely to take place in practice. Instead, it was seen as organisational formalization activity. Its product and service development processes required various formats of documentation and demanded multiple authorisation processes with superiors' requests for relatively high-fidelity prototypes. In the process harsh brevity abruptly done by superiors was reported. In-depth user research and prototyping were therefore unlikely or even ignored. Those are illustrated as follows:

"There is one parable in Samsung then. If you lay this iPhone 4 flat, a volume button will appear on the screen and this can be a shutter button too. But this function was not featured in the iPhone 1 or 2 series. At that time, a Samsung engineer who was the deputy manager suggested this idea to his director. But the idea has been immediately rejected by him, and was told, 'What a meaningless idea it is! Why didn't you do more valuable research on it?'" […] there are still limitations in speaking up in Korean companies, which causes negative effects." (17)

"In the Korean company, it could be very difficult to coordinate such design workshop because it seems to be differently comprehended. Such design workshop even requires a tangible design output. […] in the case of such big design workshops, mostly a director tends to dominate it and then general managers follow up with him or her by giving a few comments. Then it is wrapped up. It looks like a school lecture. […] design process requires in-depth studies of human needs in a social science studies approach. But we don't have time to study it. Design output must be generated within a week and confirmed by the top management. Then it comes to prototyping which era meant to be the final output." (21)

Theranos: prototyping as the politicized manifestation

Theranos has been established in 2003 by a Stanford University drop-out student, Elizabeth Holmes at age 19, who fascinates Apple, and the founder of the company, Steve Jobs. It had gained great attention from the public with the company's innovative medical product and service systems (Edison followed by miniLab, a more miniaturized one); arguably claimed to offer a broad range of clinical diagnostic test services via those. While those machines use an existing blood testing technique (called 'chemiluminescent immunoassay' that has been already suggested by an academic at Cardiff University in the 1980s in the UK) the company claimed with only a couple of drops of blood collected via a finger prick, those nanotainers can collect and test the blood sample for diagnosis of a hundred of diseases. However, in 2015 a medical research professor, John Ioannidis, Eleftherios Diamandis and journalist John Carreyrou raised questions about the validity of the company's technology. Soon later all technologies the company proposed were revealed as not valid or fake. By June 2016, the founder, Holmes's net worth had fallen to nothing from $4.5 billion. Then, the company also eventually vanished on September 4, 2018, after several years of lawsuits, and sanctions.

Autocratic leadership and limited comprehension of design

While the company's DPSS had gained such great attention from the public, the founder, Holmes had been also famed as a representative female figurehead who could be outstanding in such a male-dominated business world. But at the same time, her eccentric characteristics adopting partial male traits in her public presence had also gained attention (e.g. the product, Edison branded with the historically noticeable male inventor). But her characteristics were reflected in her relentlessly autocratic leadership and lack of work ethic (Dundes, et al., 2019).

In the prototyping process, her eccentric traits were also presented as a lack of professional empathy, shown limited understanding of design and a lack of work ethic. Inspired by Apple's design, Holmes broadly mimicked Apple's approaches in terms of design, and personal and corporate branding – e.g. the founder claimed the company's system would have to be 'the iPod of health care. But her understanding of design was limited only to design as styling or form-giving. Her relentless inquiries to its design group present the evidence in the following parable:

*"Ana (*former Apple designer, Ana Arriola who was recruited as the chief design architect in 2007*) was responsible for the overall look and feel of the Edison. Elizabeth wanted a software touchscreen similar to the iPhone's and a sleek outer case for the machine. The case, she decreed, should have two colours separated by a diagonal cut, like the original iMac. But unlike that first iMac, it couldn't be translucent. It had to hide the robotic arm and the rest of Edison's innards."* (Carreyrou, 2018: p31)

Exploitation of prototypes

The company seemingly well embedded a prototyping-driven approach across its product and service development process, seen as a design-centred organisation (Straker, et al., 2021). But the company willfully exploit its prototyping process and the outcomes. Once the first version of the prototype, called, Theranos 1.0 was made, the company prioritized using it to validate its business viability first: with the malfunctioned prototype, the company sought to obtain a license on the blood testing technology from pharmaceutical companies, gain attention from the public through a media, and for recruiting professionals. An anecdote on a malfunctioned prototype used for recruiting Edmond (called Ed) Ku, a chief engineer of the company illustrates that.

"A member of Theranos's board had recently approached him(Ed) about taking over engineering at the start-up. If he accepted the job, his task would be to turn the Theranos 1.0 prototype into a viable product the company could commercialize […] It didn't take Ed long to realize that Theranos was the toughest engineering challenge he'd ever tackled. His experience was in electronics, not medical devices. And the prototype he'd inherited didn't work. It was more like a mock-up of what Elizabeth had in mind. He had to turn the mock-up into a functioning device." (Carreyrou, 2018: p19)

Showcased prototypes

Holmes showed great talent in raising ventures from high-profile investors with the exploitation of quirky, malfunctioned prototypes. The amount of venture capital the company collected was recorded at more than US$700 million and the company's valuation reached a peak of up to $10 billion between 2013 and 2014. Amid the business success of the company, its other prototype had been wilfully exploited to present the founder's delusional vision and to uphold her socio-political status quo by realising a home-based miniaturised laboratory, called minilab, which has never been technically validated. Amid increasing dubiousness about the technologies presented in its prototypes, the company invited the vice president of the US, Joe Biden (current US president) to the company to gain more public attention. To impress him the company created a fake lab that was otherwise fully automated, by lining up malfunctioning prototypes of miniLab on the shelves of the fake lab.

*"Holmes and Balwanin wanted to impress the vice president (*Joe Biden*) with a vision of cutting-edge, completely automated laboratory. So instead of showing him the actual lab, they created a fake one […] the date of the visit, most members of the lab were instructed to stay home while a few local news photographers and television cameras were allowed into the building to ensure the event got some press. Holmes took the vice president on a tour of the facility and showed him the fake automated lab."* (Carreyrou, 2018: p265)

Implications

The analysis of the three cases now answers the research question iii) how those organisational components and barriers might impact the prototyping process and organisational material practice as a whole.

The unknowns and dominant analogies in the design practice The analysis of the finding demonstrated that at the beginning of such a competitive race of digital innovation, the increasing need for considering heterogeneous components in the generative design practice (digital artefact design) is a major source of organizational concerns on increasing complexity and uncertainty: i.e. *heterogeneous components considered in the generative design practice as the unknown.* An organisation with a lack of generative capacity, therefore, tends to show its incompetency in managing DPSS projects. Adhering to dominant design analogies and dominant logic in the design processes can constrain design groups' autonomous design problem-solving that is otherwise performed by individual designers' professionalism in an open-ended organizational environment. The case analysis demonstrated that such an organizational environment can even cause 'design fixation' in prototyping, which may perhaps lead to similar designs in final design outputs (Youmans, 2011; Crilly, 2015): Samsung's top management's high demands for high-fidelity prototypes within a short time (such organisational atmosphere and conflicts with Apple between 2011 and 2018; similar looks and feels of Samsung product and service designs with Apple's.

Prototyping as an organisational material practice that mirrors an organisation's bureaucratic approaches to managing the unknowns The findings show that the prototyping process can play a role as a bureaucratic instrument to manage such unknowns in such complex design practices, even seen as part of organizational formalization. Characteristics of the bureaucratic instruments adopted in the prototyping process present such evidencing indicator: how an organisation may formalise its material practice to cope with emerging uncertainty and complexity, by requesting a range of organisational formalisation in prototyping. These can be seen broadly, as coercive or enabling types (Adler & Borys, 1996). As evidenced in the case studies, hierarchical and dominant logics in design processes likely utilize coercive types of organisational formalisation to deal with such unknown factors in the design process: continuous requests of documentation, calling for the best high-fidelity prototype, sought by the top management (Samsung); prototyping as a part of the mundane process in a complex web of power structures (peripheral prototyping in Sony), or completely misleading prototyping processes or exploited prototyping outcomes for political showcasing (Theranos).

Oxymoron in prototyping: coping with the unknown vs. exploiting the unknown Digital artefact prototyping involves highly dynamic and discursive design practice that should cope with a range of unknown factors in the generative design process. It can thus lead an organisation to present its tacit features explicitly in the design process, compared to static and linear design practices. Under the condition of such increasing unknown factors in the design practice, such tacit organisational attitudes related to autocratic and hierarchical power structure can be reflected in how it utilises its bureaucratic instruments: e.g. coercive bureaucratic instruments to best minimise risks from taking such unknowns. In this condition, prototyping can be purposely manipulated or misled in an exploitative manner by one who considers the unknown as his/her opportunity to uphold the status quo. Experiential learning and novelty of a design output are unlikely to be considered; instead, prototyping is seen as part of formality which can highlight the presence of such powers: high-fidelity prototypes sought the top management's approvals, (Samsung); and staged prototypes to present a politicized leader's social and political status- quo (Theranos).

This research confirmed that prototyping the digital artefact (e.g. DPSS) is socio-material practice accomplished through a series of organizational discourses between multiple artefacts (e.g. hardware, software, design practice etc.) (Suchman, et al., 2002; Orlikowski & Scott, 2008). However, coupled with such conventional organizational assumptions, as opposed to generative ones, increasing unknown factors from dynamics in the digital artefact design practices have an organisation with a lack of generative capacity present its delusional vision in an exploitative manner by presenting its dubious design outputs: the unknown is thus likely to be exploited; not coped with – i.e. oxymoron in prototyping.

Concluding remarks

This exploratory study demonstrated how prototyping can mirror key features of an organisation as an organisational material practice. Such features can prominently appear in a condition of increasing unknown factors in the digital artefact design practice (e.g. DPSS practice), which are unlikely to appear in a static and homogeneous condition; then it can be miscomprehended, misled or purposefully exploited. It indicates that such organisational concerns about unknown factors can become a major source of a politicized design process coupled with an organisation's bureaucratic manner.

Yet, findings from the analysis of a limited range of qualitative data sources leave unanswered questions on how such challenges from the generative and heterogeneous design practice can be tackled in a 'designerly' way, and how such oxymoron in prototyping (e.g. experiential learning for coping with the unknown vs. exploitative manipulation with the ignorance of the unknown) can be embraced in actual organizational settings. Then it presents another concern on how future organisations might be able to deal with such increasing demands for experiential learning from prototyping with little concerns about such organisational manipulation in a real organisational context.

Concerning this, this research suggests follow-up studies on how the management of generative and heterogeneous design practices might have to be approached in association with digital artefact design with which DPSS is associated. To suggest a comprehensive framework that can account for a prototyping-driven organisation in a digital age (e.g. design thinking organizational culture in the digital age), various types of digital artefact design practices by different organizational contexts (e.g. size, industry, types of offerings etc.) need to be examined empirically.

References

Adler, P. & Borys, B., 1996. Two types of bureaucracy: Enabling and coercive. Administrative science quarterly, Volume 41, pp. 61-89.

Adler, P. & Winograd, T., 1992. The usability challgenge. In: P. S.Adler & T. Winograd, eds. Usability: Turning technologies into tools. New York;Oxford: Oxford University Press, pp. 3-14.

Andrew, J. P. & Sirkin, H. L., 2006. Payback: Reaping the rewards of innovation. S.l.:Harvard Business School Press.

Avital, M. & Te'Eni, D., 2009. From generative fit to generative capacity: exploring an emerging dimension of information systems design and task performance. Information systems journal, 19(4), pp. 345-367.

Bettis, R. & Prahalad, C., 1995. The dominant logic: Retrospective and extension. Strategic management journal, 16(1), pp. 5-14.

Bogers, M. & Horst, W., 2013. Collaborative Prototyping: Cross-Fertilization of Knowledge in Prototype-Driven Problem Solving. Journal of product innovation management, 31(4), p. 744–764.

Boland, J. R. J., Lyytinen, K. & Yoo, Y., 2007. Wakes of Innovation in Project Networks: The Case of Digital 3-D Representations in Architecture, Engineering, and Construction. Organization Science, 18(4.), pp. 631-647.

Boer, H. & During, W. E., 2001. Innovation, what innovation? A comparison between product, process and organizational innovation. International Journal of Technology Management, Volume 22, pp. 83-107.

Bowen, G.A., 2009. Document analysis as a qualitative research method. Qualitative research journal, 9(2), pp.27-40.

Braun, V. & Clarke, V., 2006. Using thematic analysis in psychology. Qualitative research in psychology, 3(2), pp. 77-101.

Brown, T. & Wyatt, J., 2010. Design Thinking for Social Innovation. Stanford Social Innovation Review, Issue winter, pp. 30-35.

Camburn, B. et al., 2017. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science, 3(13).

Carreyrou, J., 2018. Bad Blood: Secrets and Lies in a Silicon Valley Startup. S.l.:Picador.

Chang, S., 2008. Sony vs." Samsung: the inside story of the electronics Giants" battle for global supremacy. S.l.:HJ: Wiley.

Crilly, N., 2015. Fixation and creativity in concept development: The attitudes and practices of expert designers. Design Studies, Volume 38, pp. 54-91.

Dundes, L., Buitelaar, M. & Streiff, Z., 2019. Bad Witches: Gender and the Downfall of Elizabeth Holmes of Theranos and Disney's Maleficent. Social Sciences, 8(6), pp. 1-17.

Elsbach, K. D. & Stigliani, I., 2018. Design Thinking and Organizational Culture: A Review and Framework for Future Research. Journal of Management, 44(6), p. 2274–2306.

Garud, R., Jain, S. & Tuertscher, P., 2008. Incomplete by design and designing for incompleteness. Organization Studies, 29(3), pp. 351-371.

Gibson, W. And Brown, A., 2009. Working with qualitative data. Sage.

Grönroos, C., 2006. Adopting a service logic for marketing. Marketing theory, 6(3), pp. 317-333.

Hendler, S., 2019. Digital-physical product development: a qualitative analysis. European Journal of Innovation Management, 22(2), pp. 315-334.

Junginger, S., 2008. Product development as a vehicle for organizational change. Design issues, 24(1), pp. 26-35.

Kallinikos, J. A. A. a. M. A., 2013. The Ambivalent Ontology of Digital Artifacts. Mis Quarterly, 37(2), pp. 357-370.

Orlikowski, W.J. and Scott, S.V., 2008. 10 sociomateriality: challenging the separation of technology, work and organization. Academy of Management annals, 2(1), pp.433-474.

O'Reilly, M. & Kiyimba, N., 2015. Advanced qualitative research: A guide to using theory. S.l.:Sage.

Nagaraj, V., Berente, N., Lyytinen, K. & Gaskin, J., 2020. Team Design Thinking, Product Innovativeness, and the Moderating Role of Problem Unfamiliarity. Journal of product innovation management, 37(4), p. 297–323.

Nonaka, I., 1994. A Dynamic Theory of Organizational Knowledge Creation. Organization Science, 5(1), pp. 14-37

Nylén, D. and Holmström, J., 2015. Digital innovation strategy: A framework for diagnosing and improving digital product and service innovation. Business Horizons, 58(1), pp.57-67.

Rousseau, D.M., Manning, J. And Denyer, D., 2008. 11 Evidence in management and organizational science: assembling the field's full weight of scientific knowledge through syntheses. The academy of management annals, 2(1), pp.475-515.

Ruvald, R., Larsson, A., Askling, C. J. & Bertoni, A., 2020. PSS design innovation: prototyping in practice. S.l., Cambridge University Press., pp. 1355-1364.

Schrage, M., 1996. Cultures of prototyping. Bringing design to software, 4(1), pp. 1-11.

Singh, P. P., 2011. Can Sony succeed where Sony-Ericsson partnership failed? [Online] Available at: https://www.bbc.co.uk/news/mobile/business-15285258 [Accessed 25 April 2021].

Smith, M., 2014. Sony sells its VAIO PC business, is splitting TV arm into a separate company. [Online] Available at: https://www.engadget.com/2014-02-06-sony-sells-vaio.html [Accessed 25 April 2021].

Straker, K., Peel, S., Nusem, E. & Wrigley, C., 2021. Designing a dangerous unicorn: Lessons from the Theranos case. Business Horizons, 64(4), pp. 525-536.

Suchman, L., Trigg, R. & Blomberg, J., 2002. Working artefacts: ethnomethods of the prototype. British Journal of sociology, 53(2), pp. 163-179.

Ulrich, K. T., 2016. Product design and development.

Verganti, R., 2008. Design, meanings, and radical innovation: A metamodel and a research agenda. Journal of product innovation management, 25(5), pp. 436-456.

Wilson, M., 2015. Why Samsung Design Stinks BLAME STEVE JOBS SYNDROME. [Online] Available at: http://www.fastcodesign.com/3042408/why-samsung-design-stinks?utm_source=facebook [Accessed 26 January 2023].

Yin, R. K., 2009. Case Study Research: Design and Methods. 4th ed. s.l.:Sage.

Yoo, Y., 2012. Digital Materiality and the Emergence of an Evolutionary Science of the Artificial. In: P. M. Leonardi, B. A. Nardi & J. Kallinikos, eds. Materiality and Organizing: Social Interaction in a Technological World. S.l.:Oxford University Press.

Yoo, Y., Boland Jr, R. & Lyytinen, K., 2006. From organization design to organization designing. Organization Science, 17(2), pp. 215-229.

Youmans, R. J., 2011. The effects of physical prototyping and group work on the reduction of design fixation. Design studies, Volume 32, p. 115e138.

Appendices

Interviewee Tags	Job Position	Work base (at the time of the interview)	Position (Years of work experience at the time of the interview)
1	In-house Designer at HP	Singapore	Senior Level (7)
2	Samsung Designer	S. Korea	Senior Level (10)
3	User Experience Designer at SingTel and former Samsung Designer	Singapore	Senior Level (14)
4	User Experience Consultant	Singapore	Senior Level (8)
5	Design Project Lead at Panasonic UK	UK	Senior Level (Unknown)
6	Design Consultant	UK	Chairman (30)
7	Design Consultant	UK	Director (16)
8	Design Consultant	UK	Creative Director (20)
9	Samsung Semiconductor Engineer	S. Korea	Senior Level (9)

10	Entrepreneur and former Samsung Camera Engineer (formerly Samsung Techwin)	S. Korea	Executive (14)
11	Design Researcher and Consultant	UK	Senior Level (10)
12	Design Consultant	UK	Senior Level (8)
13	Project Manager and Designer	UK	Senior Level (8)
14	Service Designer	UK	Senior Level (9)
15	GUI Designer at Samsung UK	UK	Senior Level (15)
16	Design Researcher and Consultant	UK, S. Korea	Senior Level (7)
17	Global management consultant and former LG Mobile Phone Developer	S. Korea	Senior Associate (12)
18	Design Consultant	UK	Senior Level (10)
19	Interaction Designer at Microsoft and former Sony, HTC, and Nokia Designer	UK	Senior Level (10)
20	Design Consultant	UK	Director (18)
21	Samsung Designer and former Sony Designer	S. Korea	Senior Level (10)
22	Design Consultant	UK	Senior Level (7)
23	UX Designer at Google and former Sony and HTC Designer	US	Senior Level (10)

The list of Interviewees and profile

Dr Hyunwook Hwangbo

He is a lecturer of Design, Business and Technology Management (DBTM) at the Thammasat Design School (TDS), Thammasat University in Thailand, teaching a range of design management subjects (service design, design research etc.) at both BA and MA levels.
Before joining TDS, he was a research officer at the PDR International Centre for Design and Research, Cardiff Metropolitan University in the UK, and had been involved in the UK AHRC-funded research project, the development of the UK design action plan in collaboration with the UK Design Council and Manchester Metropolitan University, after completing his PhD in design at Imagination@Lancaster at Lancaster University in the UK.
Before joining the academia, he was an experienced marketer who had gained a wide range of his industry experience from multiple innovation, design and brand management relevant projects in large Korean manufacturers in the automotive and steel industries.
He is a member of a UK RADMA scholar - the 2013/14 RADMA scholarship recipient. His main research interests cover design management and innovation and design policy in a digital age, particularly focusing on digital innovation, design-centred organisation and design innovation policy in the era of digitalisation

Design prototyping for public technological solutions as a social learning practice for policymaking

Francesco Leoni, Department of Design, Politecnico di Milano
Francesco Noera, Service Design Lab, Aalborg University

Abstract

This theoretical article explores how design prototyping for technological solutions with public and social dimensions (e.g., data-centric public services) might represent a practice that fosters social learning for policymaking. The paper contributes to two contemporary strands of design research: i) design prototyping in public service innovation processes as a means for designing with institutional arrangements; ii) the role and object of design prototyping in "*design for policy*". The central thesis is that, through prototyping, the designing of public technological solutions could become a source of policy knowledge and a driver of policy learning. Therefore, the contribution of designers and design practice might go far beyond the prototyped solution and impact the policy dimension. The article develops an interdisciplinary review to support this perspective, connecting three blocks of theory: i) the enactivist framework, from cognitive science; ii) the social learning framework, from social studies of technology; and iii) the policy learning concept, from policy studies. The review highlights that an enactivist approach helps in appreciating the difference between professional design settings and other social settings in the context of technological innovation, essentially by conceiving cognition driven by the practice of design prototyping as deeply entangled within social and cultural dynamics. The article then attempts to connect theory with practice by discussing an example of service prototyping of a data-centric service for social purposes and its policy implications. In conclusion, authors propose open points for making prototyping meaningful for design for policy and designing with institutional arrangements, starting with the conscious role designers must assume toward institutional constraints during practice.

Enactivism, social learning, technological innovation, public innovation, design for policy

Already ten years ago, some authors keenly noticed that "*the landscape of design is constantly changing*" (White et al., 2012, p. 1). Until the Eighties, most design profession specialisms regarded graphics, textile, and industrial products (Julier, 2017). Later on, new design specialisations emerged with designers entering into new professional areas (e.g., interaction design, design management, service design, etc.) (Cooper, 2019; Julier, 2017; White et al., 2012), As design education and research followed these changes (Cooper, 2019), design curricula and disciplinary boundaries expanded into new areas (Buchanan, 1992). Already seventeen years ago, some scholars advanced that the product of design would no anymore be an artefact but: "[…] *an event-oriented toward a result*." (Manzini & Bertola, 2004, p. 20) and designers would play the role of "[…] *design specialists which use their specific capacities and competences to make event oriented toward a result happen*" (Manzini & Bertola, 2004, p. 22).

These specific remarks captured two paradigm shifts that characterised the design evolution toward complex systems (Buchanan, 1992): the *object of design* moving from the tangible world (i.e., artefacts) to the intangible (e.g., end-user experiences, systems of production) (Göransdotter, 2021); the design action becoming a form of collaborative problem setting and an inquiry process (Julier, 2017). These changes have resulted in design being seen as a specific form of practical intervention for responding to social problems (Markussen, 2017). Under these circumstances (Julier, 2017), design professions — e.g., UX and service designers — have increasingly entered the public sector, mainly through innovation units and labs (Bason & Schneider, 2014; Buchanan & Junginger, 2014), not only to design better services but also to address social issues in line with existing policy agendas. Designers in these contexts often use rapid prototyping to prefigure future solutions and mediate between institutions' and stakeholders' views (Kimbell & Bailey, 2017; Vink & Koskela-Huotari, 2022).

These new practices are emerging with several critical questions. For example, design is often irreconcilably presented as both a positive force and a neutral and value-free instrument (Prendeville & Koria, 2022), and factors such as aesthetic knowledge get downplayed in favour of a cognitivist view of design methods (Wetter-Edman et al., 2018). Two main areas in design research seem to be particularly touched by these critical questions: public sector innovation through service design (van der Bijl-Brouwer, 2022; Vink et al., 2017) and "design for policy" (Kimbell & Bailey, 2017; Mortati et al., 2022). The former focuses on the potential *value of service design for reflexivity* (Vink & Koskela-Huotari, 2022), where prototyping could make stakeholders involved in the public sector design process aware of existing social structures and power imbalances (Vink et al., 2017). The latter advances that design prototyping could be a space for new experimental and collaborative forms of policymaking (Deserti et al., 2020; Kimbell & Bailey, 2017) and an essential step of policymaking as designing (Villa Alvarez et al., 2020).

This paper adds to existing work on the role of design prototyping in the public/social sphere and for policymaking, asking: *what could be the value of design prototyping when used for technological solutions with public and social dimensions?*

Theoretical review

The presented interdisciplinary theoretical review aims to understand the role of design prototyping for technological innovation and solutions in public and social domains and building a conceptual tool for argumentation. The review employs an opportunistic approach by considering theory from several disciplines according to the potential roles of design prototyping at the micro-/meso-/macro-levels (Table 1).

Table 1: Synthesis of the theoretical review levels presented in this section

Level	**Design Prototyping might affect..**	**Theoretical framework or perspective considered (discipline)**
Micro	individual cognition	Enactivism (cognitive science)
Meso	social interactions and groups	Social Learning in Technological Innovation (STS)
Macro	norms and policies	Knowledge utilization in policy and policy learning (policy studies)

The enactivist framework

The *enactivist framework* (Ward et al, 2017) represents one of the most articulated critics to the *cognitivist* paradigm, hegemonic in cognitive science until recently, which conceives cognition as an individual process, situated in the brain. Cognitivism advanced that the central nervous system is analogous to a computational machine that receives inputs from the environment, utilises them to produce representations of the world and organises behaviour accordingly (Watson and Coulter, 2008). In contrast, enactivism essentially proposes that the human mind is inseparable from the functioning of an organism's body as a whole.

This proposal emerged from foundational scholars of enactivism, who were interested in studying cognition as a way to clearly distinguish between living and non-living systems (Maturana and Varela, 1987). They recognized two conditions that distinguish a living system: (1) it features *self-organisation*, since it can reproduce its own internal constitutive elements and processes, by letting in energy (impulses on sensory organs) and matter (oxygen and food) coming from the environment; (2) the self-organisation process demarcates the organism from its own environment, entailing some degree of systemic 'closure'. Such conditions imply that self-organisation is a process of mutual definition between an organism and its environment, since one would not exist in absence of the other:

"*Cognition and world are interdependently originated via the living body. [..] a cognitive being's world is not a pre-specified, external realm, represented internally by its brain, 153uti s rather a relational domain enacted or brought forth by that being in and through its mode of coupling with the environment*" (Thompson, 2016, p. xxvii).

Following the enactivism framework *cognitive processes are necessarily also social* (Di Paolo, 2018), since the environment with whom an organism couples itself is social as well as physical. While a definite enactivist description of social processes is still unsettled (McGann, 2014), enactivism is fostering a reformulation of the social side of cognition. The tacit coordination involved by social relationships (Heft, 2007) entails *the mutual co-definition of self-organizing patterns of individuals*, which synchronize and let emerge what is perceived as a shared and objective environment (Durt et al., 2017). The concept of *affordance* — i.e. the set of possibilities and the constraints that a particular environment represents for an organism (Gibson, 1966) — helps further in collocating enactivism in social dynamics. Affordances are reframed within enactivism as socially constructed and shared, because they coincide with the coupling of self-organisation patterns of different individuals (Elias, 2017; Rietveld et al. 2018).

Social Learning in Technological Innovation framework

The concept of *social learning* was developed to overcome the inadequacies of the previous deterministic accounts of sociotechnical development. Early social studies of technology conceived technology as an embodiment of social structures and values, realised by engineers and designers (Noble, 1978). Use and diffusion of technology were seen therefore as unidirectional processes, with a linear movement from designers to final users. Choices taken during design time were assumed to determine final use and its social consequences. Further research on innovation processes, however, highlighted the fact that *technical* *improvements emerge often from the very use of technologies*. Gradually mastering a particular artefact, users can apply their expertise backwards and improve the artefact itself (Sørensen, 1996).

Such research framework, labelled as *Social Learning in Technological Innovation* (SLTI) (Williams et al., 2005) highlights the circular dynamics between the creation of human expertise and technical innovation, underlining also how this 154uti s154154 s deeply embedded in wider networks of relations, between different expertise, industries, and social groups. Power and economic interests, as well as political and social conflicts were integrated as factors that influence the learning process entailed by the interaction with a technology.

SLTI pointed out that innovation coincides with the back-and-forth of different actors around technology (Stewart and Hyysalo, 2008), thus, innovation has been recognized as a process that includes designers, users, and other intermediary actors. Accordingly, the terms *innofusion* and *diffused innovation* emerged to indicate that diffusion and innovation should be considered two sides of the same historical process (Fleck, 1988; von Hippel, 1988).

The core element of the SLTI framework is that not only the design, but also the use of technology is an active process. SLTI acknowledges that social groups tend to re-collocate a new technology within their existing knowledge, practices and routines, following their interests and purposes. The process of re-collocation, called *appropriation or domestication*, is crucial to effectively use a technology within a new social environment; while implementation involves a re-shaping of the technology role itself, necessary for users to interact effectively with it. Technical systems trigger changes of social routines, which need to be adapted to construct an efficient environment of use. The users' appropriation of a new technology is therefore unavoidably social also because they acquire expertise by interacting with each other, rather than only with the technology itself.

Knowledge utilization and policy learning

The studies of knowledge utilisation for policy have a long history, particularly relevant during the 70s/80s (Radaelli, 1995) and briefly revived by the evidence-based policy movement (EPM) (Strassheim, 2018). While EPM advocated for policies to be based only on scientific evidence, knowledge utilization and recent ethnographies on public officials work (Maybin, 2016) clarified that policy-relevant knowledge is not only produced by experts (e.g., policy analysts), researchers or scientists. Policy actors might be willing to incorporate scientific/expert evidence, but are often limited in doing so because of the controversial nature of policy problems and tight time constraints for deciding and acting (Strassheim, 2018). Under such circumstances, certain policy decisions might be informed by scientific/expert knowledge, while others privilege other types of knowledge/ evidence (Wesselink et al., 2014). For these latter contexts, policy workers might privilege non-scientific but more accessible sources (Pawson, 2002; Strassheim, 2018; Tenbensel, 2006), largely relying on their experiential knowledge (Maybin, 2016). What counts as relevant policy knowledge/evidence is therefore highly dependent on specific contexts and policy problems under question, as well as the strategy of knowledge utilisation of policy workers (Wesselink et al., 2014).

These knowledge utilization practices had been regarded as the micro-foundations of policy learning. Policy learning has been considered a type of social learning that can be institutionalised to drive policy change (Hall, 1993). Accordingly, change and innovation at the policy level could be not only dependent by political power plays, but the "puzzling" of policy actor on public problems (Heclo, 1974). Policy learning became a well-established field of the policy studies and potential interpretative lens of the policy process (Dunlop et al., 2018). In contrast with knowledge utilisation, policy learning is intended to explain also unintentional dynamics of knowledge within networks of actors involved in policy (Heikkila & Gerlak, 2013). However, policy learning as explanatory variable of policy change presents limitations, since it remains difficult to isolate the causes of learning or even when learning does not occur. As a consequence, the link between policy learning and policy change remains investigated by many but never presented as obvious (Moyson, 2017).

Insights for design prototyping from the reviewed theoretical frameworks

This section highlights the main concepts and perspectives emerging from the reviewed theoretical framework, highlighting how they can support design prototyping in public/social domains and policymaking.

The concept of Co-definition: challenging status quo through prototyping

Enactivism describes the mutual shaping between organisms and environments through *co-definition,* i.e. the circular constraining of minds and environments (Di Paolo, 2018), thus confirming, through a cognitive science perspective, the active role of users in the use of artefacts. Co-definition implies that cognition and perception emerge in individuals only by interaction with their environment, which is both physical and social. At the same time, the emergence of an individual's mind is not linearly determined by the incoming stimuli. The reception of stimuli from the environment depends on individuals' self-organisations. It follows that cognition and perception are always potentially creative processes rather than mere recognition and representation of external objects (Varela et al., 2016).

The enactivist framework helps us to change how we conceive design prototyping activities. The continuative use of the same artefacts impacts the self-organisation of an individual's cognition (Kirsh, 2013). Such *'incorporation'* of tools is not automatic and depends on repeating interactions between the subject and the artefact. It represents a learning process, which also entails a profound shift in the user's mind since it changes the boundaries of what is thinkable and perceivable. Enactivism provides a strong argument for the power of design prototyping to disrupt perceptions at the micro-level through bodily and aesthetic experience (Wetter-Edman et al., 2018), which in turn might be the first step to invite stakeholders to challenge the status quo in the public sphere.

Design as social learning and co-definition processes

The SLTI framework has been applied to professional design settings, describing 155uti s155 social learning processes within wider innovation networks (Stewart & Williams, 2005).

In contrast to the claim that designers inscribe a defined set of affordances within artefacts,

SLTI has pointed out that innovation should be conceived as a continuous integration of choices outside of design and engineering laboratories (von Hippel, 2009). By considering innovation as designers' prerogative, the user-centred design theories have not entirely overcome a deterministic and linear view of innovation (Woolgar, 1991), thus missing the possibility of understanding innovation processes in broader social contexts (Bogers & West, 2012).

SLTI presents interesting affinities with the concept of co-definition from Enactivism. STLI opens new insights about the continuity between professional design and socially diffused innovation. From such a perspective, designers inscribe in artefacts a spectrum of the possibilities of affordance rather than a closed set. During diffusion, some affordances of the such spectrum are suggested to users through other channels, like printed instructions, training programs, organisational routines, etc. These explicit affordances are the more likely to be used. However, drawing on Enactivism, the affordances that the artefact furnishes to users depend ultimately on the specific co-definition enacted by the latter with their environment. It is such a process of co-definition that allows users to activate artefact-dependent 'sleeping' affordances or even create new ones.

These perspectives support the idea that design prototyping in the public/social sphere is an effective way to collectively explore and learn about a public issue. Prototypes offer more possibilities to non-expert stakeholders to take an active and creative role in the design of a policy, due to the capacity of prototypes to open different paths for co-definition to which stakeholders can react.

Design prototyping as a strategy to impact policy learning

Research has already highlighted how prototypes can be understood as tools through which professional designers reflexively orient their agency (Dalsgaard, 2017). Such role of prototypes is pointed out also in the case of team or participatory work: different expertise and points of view can interact successfully through the shared playground represented by a prototype. Indeed, research has widely recognised prototyping as a tool to synchronise a team, focusing teamwork towards realising a precise output (Star & Griesemer, 1989; Vinck & Jeantet, 1995).

Drawing on enactivism, prototyping is so effective because it allows designers to experiment with different kinds of co-definition with the environment in a rapid and trial-and-error manner (Kirsh, 2013). In this way, designers can purposely challenge what participants think and perceive, stimulating the emergence of new possibilities and ideas. The use of prototypes helps designers not only notice new affordances but actively create new ones that did not exist before the very creation of the prototype.

In policymaking, prototypes can become tools that designers use for translating between tacit experiential and professional knowledge into policy framewoks. As experiential knowledge of policy workers and civil servants is essential to translate high-level directives into actual policies and services (Maybin, 2016), design prototyping could be strategically used to increase the degree of possible choices in front of policy makers, and to integrate perspective from stakeholders active on the operational level.

An example from practice: prototyping a data-centric system for food donation

In this section, we provide an example of design prototyping practice from the experience of one of the authors, intending to provide a clear context in which our argument applies.

The example described was part of “La Cucina Collaborativa”[1], a citizen engagement project jointly developed by The Design Policy Lab (DPL), a research lab at the Department of Design (Politecnico di Milano) and Caritas Diocesana Reggio Emilia – Guastalla, a charitable organisation based in the city of Reggio Emilia (Italy). From September to December 2021, “La Cucina Collaborativa” took place in Reggio Emilia as a co-design process of circular solutions against food waste, involving more than one hundred individuals of a charitable food donation system (including diners, volunteers, representatives of food donors companies and public servants).

The rapid prototyping session represented the last steps of a broader co-design and involvement methodology that aimed to improve the food donation system delivered by Caritas against food waste. The session lasted only one afternoon and was designed by the DPL staff to refine and get feedback about one of the ideas that emerged in earlier ideation stages, involving only Caritas’ staff and volunteers. The idea prototyped had emerged previously due to stakeholders’ interest in improving the food donation systems through digitalisation and better use of digital data. The idea proposes to optimise the logistics of donated food according to the nutritional profile data of beneficiaries thanks to food warehouse management software and to customise the packages with appropriate food and specific messages from food donors (sent through QR codes on the packaging) (fig. 1).

Figure 1: Pictures from the rapid prototyping session held within La Cucina Collaborativa. Physical and digital mock-ups were used to visualize a fictional logistics dashboard interface and the packaging with the QR code.

[1] The project was funded under the call “Cross-KIC New European Bauhaus Call for Proposals for Citizen Engagement published in 2021 by EIT Food as part of New European Bauhaus. More info are available at www.designpolicy.eu/cucina-collaborativa

The prototyping of the envisioned data-centric food donation system was a way to explore a broader design opportunity area, i.e., the digital innovation of food donation, rather than the specific idea *per se*. The prototypes allowed participants to comment on the social acceptability of the proposed technological solutions, also based on their tacit and experiential knowledge as volunteers. In particular, volunteers were keen to point out that the data-centric solutions envisioned were assuming a notable level of transparency in the system, which could clash with the social stigma they knew was felt by many among the people resorting to food donation.

Conclusions: designers as conscious players in public sector prototyping

Applying the enactivist concept of *co-definition to prototyping* activities enriches the definition of design as a social learning process. Enactivism highlights a difference between professional designers and other social settings of innovation.

Design practices seem to be more aware and prepared to take advantage of the deep reflexivity, i.e. co-definition, that happens during interactions between humans and artefacts. Designers can envision to policy stakeholders future possibilities through prototyping and affordances and challenging existing institutional boundaries (Vink et al., 2017). However, in line with the SLTI framework, the difference between professional designers and users appears to be just a matter of degree; or, in other words, a more developed expertise of the strategies and resources needed to trigger reflexivity in participants of collaborative work.

On the basis of the analysis proposed here, we conclude by advancing three open points that can support the emerging innovative perspective on design prototypes in the social and public domain and for policymaking:

1) Within policymaking and public sector settings, designers should act as conscious players of institutional and political dynamics. The attention usually given by designers to non-designers as active actors in prototyping should enlarge the broader systems of governance and social structures surrounding the context of prototyping. In this sense, designers must be increasingly trained with the same soft skills and knowledge common among civil servants and social workers.

2) To point out the expertise of designers as only incrementally different from non-designers and, in parallel, to point out that professional design expertise involves an enhanced capacity of reflexively interacting with experimental artifacts, essentially means that *designers are trained into forms of knowledge connected to materiality*. The tendency to de-materialise the object of design has hindered one of the main tenets of design contribution to the social and public sphere. Dissipating the object of design may unwarrantedly suggest that design could contribute to these areas through an overly disembodied approach to cognition, leaving outside the importance of material culture and aesthetic knowledge (Wetter-Edman et al., 2018). The connection between broad governance and political levels and materiality should be something that is not only understood in experimental and artistic environments but also in rapid prototyping for collective public settings.

3) To envision a new theoretical framework on the use of design practices in policymaking, which would defend an important degree of autonomy for social actors' agency, while at the same time avoiding to postulate a radical individualist conception of agency, as in neoliberal policies (Fraser, 2011).

References

Bason, C., Schneider, A. (2014). Public design in global perspective: Empirical trends. In Design for policy (pp. 23–40). Gower Publishing.

Bogers, M., West, J. (2012). Managing Distributed Innovation: Strategic Utilization of Open and User Innovation. , 21(1), 61–75.

Buchanan, C., & Junginger, S. (2014). (Service) Design and Policy Making. In D. Sangiorgi, A. Prendiville, & A. Rickett (Eds.), Mapping and developing Service Design Research in the UK (pp. 48–49). Arts & Humanities Research Council.

Buchanan, R. (1992). Wicked Problems in Design Thinking. Design Issues, 8(2), 5–21. http://www.jstor.org/stable/1511637

Cooper, R. (2019). Design research – Its 50-year transformation. Design Studies, 65(xxxx), 6–17. https://doi.org/10.1016/j.destud.2019.10.002

Dalsgaard, P. (2017). Instruments of Inquiry: Understanding the Nature and Role of Tools in Design. International Journal of Design, 11.

Deserti, A., Rizzo, F., & Smallman, M. (2020). Experimenting with co-design in STI policy making. Policy Design and Practice, 3(2), 135–149.

Di Paolo, E. A. (2018). The Enactive Conception of Life. In: Newen, A., De Bruin, L., Gallagher, S. (eds.). The Oxford Handbook of 4E Cognition. Oxford: Oxford University Press.

Dunlop, C. A., & Radaelli, C. M. (2020). Policy Learning in Comparative Policy Analysis. Journal of Comparative Policy Analysis: Research and Practice, 00(00), 1–22. https://doi.org/10.1080/13876988.2020.1762077

Dunlop, C. A., Radaelli, C. M., & Trein, P. (2018). Introduction: The family tree of policy learning. In Learning in public policy (pp. 1–25). Springer.

Durt, C., Fuchs, T., Tewes, C., ed. (2017). Embodiment, Enaction, and Culture: Investigating the Constitution of the Shared World. Cambridge, Massachusetts: MIT Press.

Elias, J. (2017). The Extent of Our Abilities: The Presence, Salience, and Sociality of Affordances. In: Durt, C., Fuchs, T., Tewes, C. (ed.). Embodiment, Enaction, and Culture: Investigating the Constitution of the Shared World. Cambridge, Massachusetts: MIT Press, pp. 245-256.

Fleck, J. (1988). Innofusion or Diffusation? Nature of Technological Developments in Robotics. Working Paper, Programme on Information and Communications Technologies, Edinburgh.

Fraser, N. (2011). Marketization, Social Protection, Emancipation: Toward a Neo-Polanyian Conception of Capitalist Crisis. In C. Calhoun & G. Derluguian (Ed.), Business as Usual:

The Roots of the Global Financial Meltdown (pp. 137-158). New York, USA: New York University Press.

Gibson, J. J. (1966). The Senses Considered as Perceptual Systems. Allen and Unwin, London.

Göransdotter, M. (2021). Transitional Design Histories: Presenting History in Design. Nordes, 187–196.

Hall, P. A. (1993). Policy Paradigms, Social Learning, and the State: The Case of Economic Policymaking in Britain. Comparative Politics, 25(3), 275. https://doi.org/10.2307/422246

Heclo, H. (1974). Modern social politics in Britain and Sweden. Yale University Press.

Heft, H. (2007). The Social Constitution of Perceiver-Environment Reciprocity. Ecological Psychology, 19(2), pp. 85-105.

Julier, G. (2017). Economies of Design. SAGE Publications.

Kimbell, L., & Bailey, J. (2017). Prototyping and the new spirit of policy-making. CoDesign, 13(3), 214–226.

Kirsh, D. (2013). Embodied Cognition and The Magical Future of Interaction Design. ACM Trans. Computer-Human Interaction 20(1), Article 3. URL: https://quote.ucsd.edu/cogs1/files/2012/09/Kirsh-Final-acm_reading.pdf

Manzini, E., & Bertola, P. (2004). Design Multiverso. Appunti di fenomenologia del design. Edizioni polidesign.

Markussen, T. (2017). Disentangling 'the social' in social design's engagement with the public realm. CoDesign, 13(3), 160–174. https://doi.org/10.1080/15710882.2017.1355001

Maturana, H. and Varela, F. (1987). The Tree of Knowledge: The Biological Roots of Human Understanding. Boston: New Science Library.

Maybin, J. (2016). Producing health policy: Knowledge and knowing in government policy work. Springer.

McGann, M. (2014). Enacting a social ecology: radically embodied intersubjectivity. Frontiers in Psychology, 5.

Mortati, M., Mullagh, L., & Schmidt, S. (2022). Design-led policy and governance in practice: a global perspective. Policy Design and Practice, 1–11. https://doi.org/10.1080/25741292.2022.2152592

Moyson, S. (2017). Cognition and policy change: The consistency of policy learning in the advocacy coalition framework. Policy and Society, 36(2), 320–344. https://doi.org/10.1080/14494035.2017.1322259

Noble, D. (1978). Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor. Politics & Society, 8(3-4), pp. 313-347.

Pawson, R. (2002). Evidence-based Policy: The Promise of `Realist Synthesis'. Evaluation, 8(3), 340–358. https://doi.org/10.1177/135638902401462448

Prendeville, S., & Koria, M. (2022). Design Discourses of Transformation. She Ji, 8(1), 65–92. https://doi.org/10.1016/j.sheji.2022.01.002

Radaelli, C. M. (1995). The role of knowledge in the policy process. Journal of European Public Policy, 2(2), 159–183. https://doi.org/10.1080/13501769508406981

Rietveld, Erik, Damiaan Denys, and Maarten Van Westen (2018). Ecological-Enactive Cognition as engaging with a field of relevant affordances: The Skilled Intentionality Framework (SIF)', in Albert Newen, Leon De Bruin, and Shaun Gallagher (eds), The Oxford Handbook of 4E Cognition, Oxford Library of Psychology (2018; online edn, Oxford Academic, 9 Oct. 2018)

Sørensen, K. (1996). Learning Technology, Constructing Culture. Sociotechnical Change as Social Learning. STS-arbeidsnotat 18/96. URL:https://www.ntnu.no/c/document_library/get_file?uuid=3ecdf343-69b7-4544-a5a3-ae9accca1e67&groupId=10265 [Accessed 22 Jan. 2023].

Star, S. L., and Griesemer, J. R. (1989). Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social Studies of Science, 19(3), pp. 387-420.

Stewart, J., and Williams, R. (2005). The Wrong Trousers? Beyond the Design Fallacy: Social Learning and the User. In: User Involvement in Innovation Processes. Strategies and Limitations from a Socio-technical Perspective. Harald Rohracher, Profil-Verlag, Munich, 2005.

Stewart, J., Hyysalo, S. (2008). Intermediaries, users and social learning in technological innovation. International Journal of Innovation Management, 12(3), 295–325.

Strassheim, H. (2018). Policy as a body of expertise. In Handbook on Policy, Process and Governing. Edward Elgar Publishing.

Tenbensel, T. (2006). Policy knowledge for policy work. The Work of Policy: An International Survey, 199–216.

Thompson, E. (2016). Introduction to the Revised Edition. In: Varela, F. J., Thopmson E., E. Rosch, E., The Embodied Mind. Cambridge, Massachusetts: MIT Press.

Van der Bijl-Brouwer, M. (2022). Service Designing for Human Relationships to Positively Enable Social Systemic Change. International Journal of Design, 16(1), 23–34. https://doi.org/10.57698/v16i1.02

Varela, F., Thompson, E., Rosch, E. (2016). The Embodied Mind. Cambridge, Massachusetts: MIT Press.

Villa Alvarez, D. P., Auricchio, V., & Mortati, M. (2020). Design prototyping for policymaking. DRS2020: Synergy, 2, 11–14. https://doi.org/10.21606/drs.2020.271

Vinck, D., and Jeantet, A. (1995). Mediating and Commissioning Objects in The Sociotechnical Process of Product Design: A conceptual approach. Management and new technology: Design, networks and strategies, 2, pp. 111-129.

Vink, J., & Koskela-Huotari, K. (2022). Building Reflexivity Using Service Design Methods. Journal of Service Research, 25(3), 371–389.

Vink, J., Tronvoll, B., Edvardsson, B., Wetter-Edman, K., & Aguirre, M. (2017). Service Ecosystem Design: Doing Institutional Work through Design. June.

Von Hippel, E. (1988). Sources of Innovation. New York NY: Oxford University Press.

Von Hippel, E. (2009). Democratizing Innovation: The Evolving Phenomenon of User Innovation. International Journal of Innovation Science, Vol. 1 No. 1, pp. 29-40.

Ward, D., Silverman, D., Villalobos, M. (2017). Introduction: The Varieties of Enactivism. Topoi 36, pp.365–375.

Watson, R. and Coulter, J. (2008). The debate over cognitivism. Theory, Culture & Society, 25 (2), 1–17.

Wesselink, A., Colebatch, H. K., & Pearce, W. (2014). Evidence and policy: discourses, meanings and practices. Policy Sciences, 47(4), 339–344. https://doi.org/10.1007/s11077-014-9209-2

Wetter-Edman, K., Vink, J., & Blomkvist, J. (2017). Staging aesthetic disruption through design methods for service innovation. Design Studies, 55, 5-26.

White, H., Holmlid, S., Wetter Edman, K., Pacenti, E., & Mager, B. (2012). What Do Tomorrow's Service Designers Need to Know. Proceeding of SERVDES 2012.

Williams, R., Stewart, J., & Slack, R. (2005). Social learning in technological innovation: Experimenting with information and communication technologies. Edward Elgar Publishing.

Woolgar, S. (1991). Configuring the User: The Case of Usability Trials. In: Law, J. (ed.), A Sociology of Monsters. Essays on Power, Technology and Domination, London: Routledge, pp. 57-102.

Francesco Leoni

PhD in design and researcher with a background in communication design (Politecnico di Milano, IUAV), currently working as a research fellow for the Department of Design in Politecnico di Milano. He is a permanent research staff of two official research entities in the Department of Design: the Design Policy Lab, a policy lab and research unit focused on “design for policy” (www.designpolicy.eu), and Polifactory, the official makerspace/fab-lab of Politecnico di Milano (www.polifactory.polimi.it). His work contributes to the field of “data for policy”, by exploring the relationship between the use of non-traditional data and data-centric innovations in the public sector and policymaking. In conducting this exploration, he adopts the lens of “design for policy”, a subset of the design discipline that investigates the relationship between designing and policymaking by operationalising policy concepts and theories from literature through QUAL/QUANT methodological frameworks and specific methods.

Francesco Noera

Design research affiliate at the Service Design Lab, Aalborg University. He holds a B.A. in Anthropology (Alma Mater Studiorum – Università di Bologna), a M.Sc. in Science and Technology Studies (The University of Edinburgh) and a Pg.Dip. in Service Design (Politecnico di Milano). His expertise includes qualitative research, service design and innovation management. Currently, he is working as Acceleration and Innovation Specialist in Fondazione REI, the public-private institution which manages the Technopole of Reggio Emilia, in turn a node of Emilia-Romagna High Technology Network. His research interest is innovating design practices by drawing on insights from other disciplines; he is especially focused on harmonizing theories of embodiment, either from social and cognitive sciences, with theories of sociotechnical innovation. Such harmonization aims at opening up an experimental space for new applied practices and procedures, either considering methods for facilitating workshops, designing of tools as canvas and prototypes, or training of designers themselves.

Prototyping in service design: the case of CHECKD. – an automatic booth for Covid-19 testing

Daniela Selloni, Department of Design, Politecnico di Milano
Serena Stefanoni, Department of Design, Politecnico di Milano

Abstract

Prototyping is a core phase in the design process. In service design, this activity has been less explored: differently from physical products, services entail the representation of complex systems of people, contexts, artefacts and interactions. Service prototyping poses a great challenge to designers who have to manage a combination of tangible and intangible aspects which spans through time. Drawing on the background knowledge available on the topic, this paper discusses a service prototyping case study: named Checkd., it concerns the development of an automatic booth for Covid-19 testing. Prior to prototyping, a context analysis and user research were carried out and co-design workshops were held to refine the idea. Then, two rounds of service prototyping were accomplished. In the first one a service encounter (sample collection procedure) was tested with users, adopting the experience prototyping technique and low-fidelity props. The second round reproduced the complete service experience, adopting a service walkthrough technique and mixed-fidelity artefacts, where participants could understand the full journey in a situated way.
Building upon these prototypes, we elaborated three main considerations. One first takeaway deals with the relationship between purpose and fidelity level. Low/mixed fidelity prototypes drove a purpose change, from evaluative to explorative, as the ‘unfinished’ nature of the set-up allowed more user interpretation and proposal of personal ideas. A second takeaway concerns iterations that must be planned with different levels of focus and resolution, keeping the flow of co-design and re-design open allows to fully approach service complexity. A third takeaway is about the role(s) of the designer/author. He/she should be more than a mere facilitator by enacting mechanisms of the experience itself: continuously shifting roles and relating with a variety of users, he/she becomes an advocate of the whole user experience and, more in general, an advocate of a broader prototyping culture.

Service design; Service prototyping; Experience prototyping; Service walkthrough; Co-design

Background knowledge about prototyping in service design

Prototyping is a well-established area of the design practice and process (McElroy, 2017; Kelley, 2001; Budde et al.,1992; Floyd, 1984). The design research approaches this subject in different ways, proposing a variety of perspectives and frameworks (to mention a few: Sanders and Stappers, 2014; McCurdy et al., 2006; Kammersgaard, 1983). In addition, most of the available studies focus on product (both physical and digital) and interaction design (McElroy, 2016).

Less explored, instead, is prototyping in the service design field (Blomkvist, 2011; Passera et al., 2012). Most of the existing knowledge comes from the dissertations of Blomkvist (2011,

2014) who explores the difference with 'traditional' prototyping and identifies the challenges that service designers have to face when approaching such activity. Prototyping services entails, in fact, replicating complete, holistic experiences, where highly elaborated systems of both tangible and intangible elements come together (Blomkvist, 2011, 2014; Passera et al., 2012). The intangible nature of a service itself dependent of time and inherently unique and personal (Zomerdijk & Voss, 2010) raises the complexity of service prototyping, but at the same time it is a promising field of research, where investigation is still largely needed (Blomkvist, 2011).

Blomkvist (2014) considers service prototypes any representation of a future situation, either of them being sketched ('definite') or enacted ('ongoing') and defines them as surrogates that exists in a liminal state, that can be tested and explored freely and without time limitation. He also addresses other critical aspects of service prototyping (Blomkvist, 2011), such as benefits and levels of participation and the connection with the service environment (the so-called servicescape) and experiences (Blomkvist, 2014). In conjunction with other researchers, he also proposes a new technique, the service walkthrough (Arvola et al., 2012; Blomkvist, 2011; Blomkvist et al., 2012; Blomkvist & Bode, 2012; Blomkvist, 2014; Blomkvist & Arvola, 2014), building upon the already existing experience prototype, bodystorming and pluralistic walkthrough techniques (Buchenau & Suri, 2000). The service walkthrough can bring to life, in a somewhat realistic way, a service in its completeness (end-to-end) by having people physically enacting the sequence of carefully orchestrated steps of the service and live the experience as close as possible to the ideal version.

Finally, and most importantly for the scope of this paper, he outlines a framework for service prototyping, highlighting its multiple dimensions: position in process, purpose, audience, technique, fidelity and representation (Blomkvist, 2011). Passera et. Al. (2012), building upon Blomkvist's work, propose the 'Service Prototyping Practical Framework', which is characterised by a more applied perspective. They provide a series of guidelines, defining them as an "aid for thinking and asking fundamental questions when prototyping" (Passera et al., 2012, p.5) and we believe that they are extremely useful to orient the work and better plan the whole process.

Here is a summary of such framework elaborated by Passera et al. (2012).

First, like in the original version, the position in the process and the purpose of the prototype (exploration, evaluation, or communication) are set, basing on the question 'what is the service hypothesis I am testing? What do I want to learn?'; following, it approaches the Author (the person who defines and plans the prototype set up) and the resources ('what is the simplest available way to implement the best possible experiment? To what resources do we have access?'), also outlining a set of heuristics (location, users, staff, props) to assess them; as a fourth point, they mention the technique ('which technique? How to plan it? What data can I expect?'); then, the fidelity/resolution aspect is approached, by suggesting the development of a 'resolution graph' that can support in keeping each service dimension separate for a better understanding ('what needs to look and feel verisimilar for the prototype to succeed? What needs to be functional, and to what degree?'); then, they analyse the validity ('how generalizable are the results of the experiment? What exactly did I learn from what I tested?'); finally, plausibility is evaluated in relation with the audience of the prototype itself ('was the prototype plausible for my audience? Was their feedback reliable?').

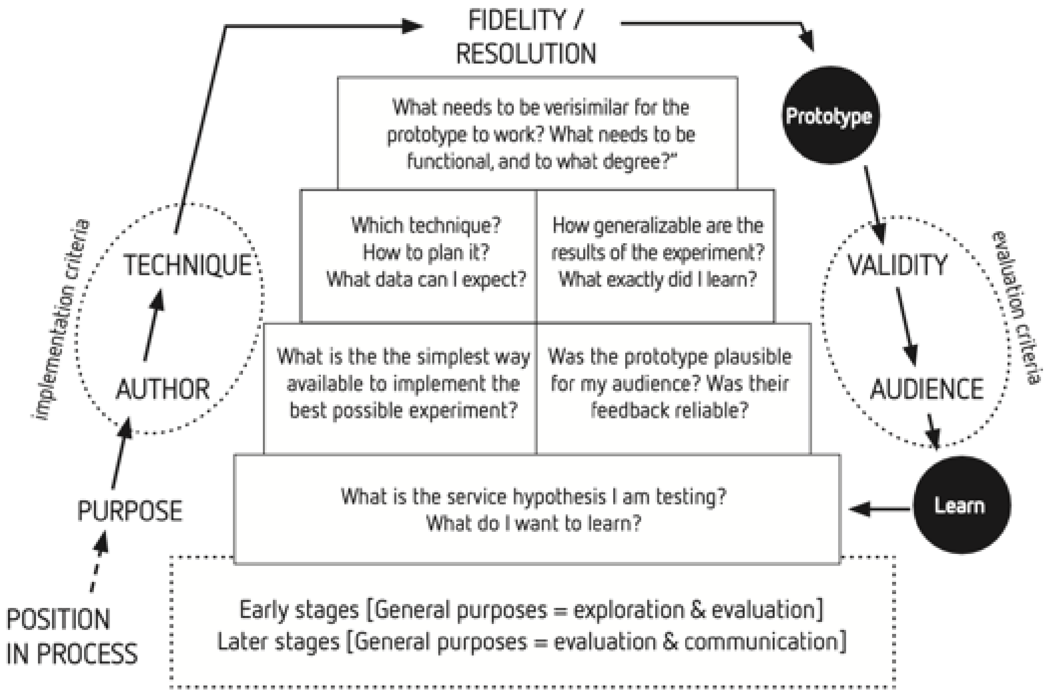


Figure 1: The Service Prototyping Practical Framework developed by Passera et al. (2012).

This paper precisely builds upon the Service Prototyping Framework developed by Passera et al. (2012) to discuss the case study of Checkd. This project's context was an experimental master thesis, done in collaboration multiple actors: the Department of Chemistry and Applied Biosciences at the Eidgenössische Technische Hochschule (ETH) Zürich (as the main host institution), Diaxxo AG, a biotech startup and spin-off of ETH's Functional Materials Laboratory, PD|Z, a group within ETH that focuses on system-oriented product development and innovation and the Department of Design of Politecnico di Milano supervising the whole thesis. The main objective was to leverage the innovative technologies advanced by the startup Diaxxo AG (devices capable of running PCR[1] analysis in a very small amount of time) to develop an automatic booth for Covid-19 testing, to be placed in public spaces, by designing the different elements related both to the product and the service experience.

The Case Study of Checkd

The design of Checkd. Encompassed 3 main phases: context and user research; co-design and concept refinement; prototyping. For the purposes of this paper, we will briefly describe the first two phases and we will focus mainly on the third phase, where a prototype was made operational in short time, aiming to lay the foundation for a whole product-service system solution to be implemented in future.

[1] PCR stands for Polymerase Chain Reaction a method widely used to rapidly make millions to billions of copies (complete or partial) of a specific DNA sample.

Phase 1: Context and user research

The first phase explored Covid-19 testing options (antigen and molecular). We shared a survey with a diverse pool of people: motivations, feelings and behaviours when experiencing both solutions were captured and integrated with desk research into ‘testing experience maps’, useful to analyse pain and pleasure points.

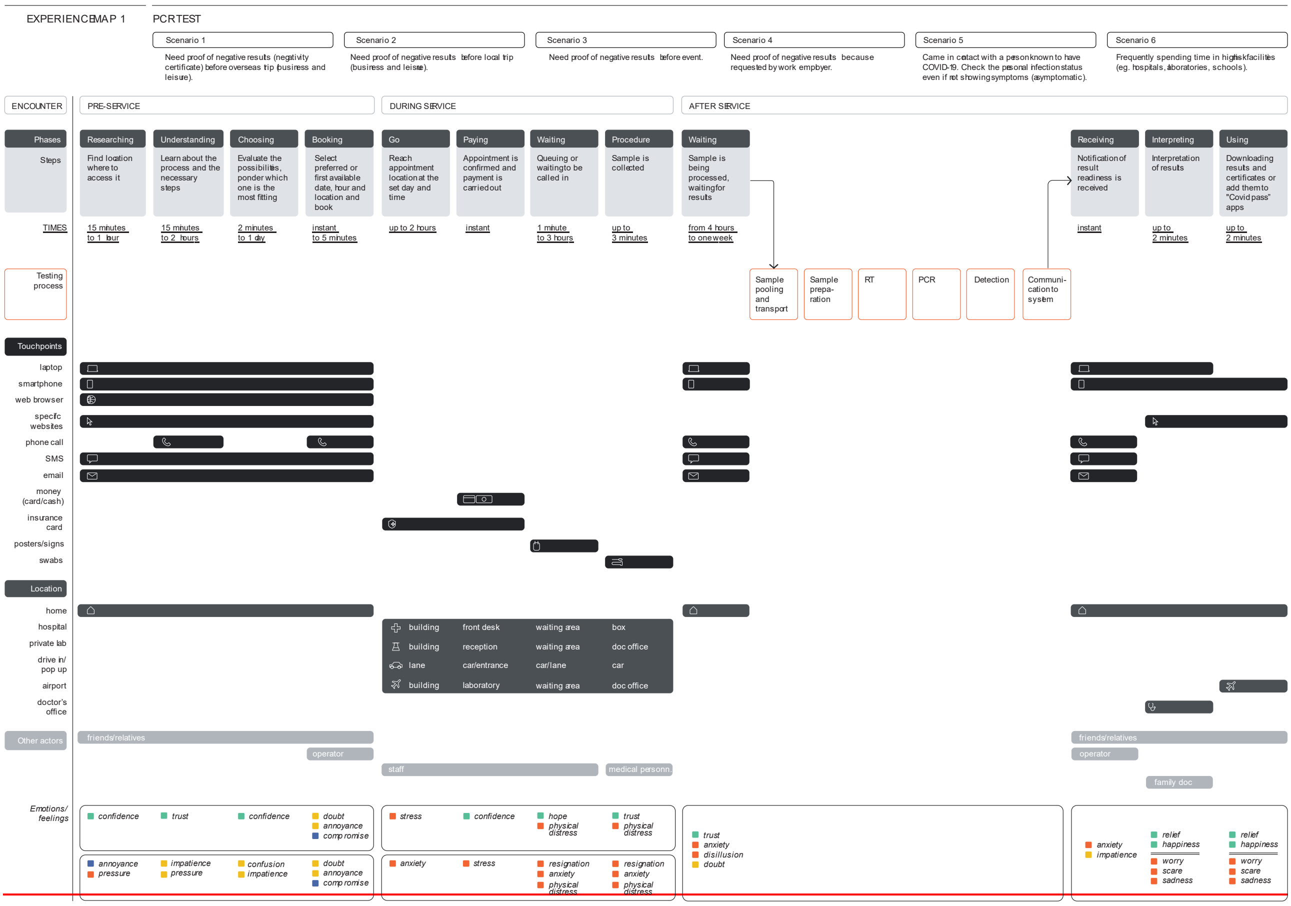


Figure 2: The testing experience map concerning the PCR/molecular test typology.

In parallel, we analysed the rough existing concept for the booth proposed by the startup: we expanded on the journey linked to it, highlighting what did work, what did not and future opportunities.The outputs of this first phase, discussed with all the stakeholders, created the basis for the ensuing co-design stage.

Phase 2: Co-design and concept refinement

We held 7 co-design workshops with 16 participants, identified among possible user categories. Virtually ‘anyone’ could have been a user, but, building upon the startup’s initial work, we decided to focus on travellers as the suggested location for the booths would be airports and train stations.

The workshops aimed to guide the choices for developing an effective and pleasant user experience, as well as discuss structural features of the booth and user interactions with technological elements.

The sessions were structured in three parts: warm-up, intermezzo, and core.

After introductory activities in the ‘warm-up’, participants’ first impressions about a ‘booth for disease testing’ were captured in an individual activity named ‘intermezzo’ (tool shown in figure 3).

Figure 3: The tool used in the “intermezzo” phase.

In the core, we presented a draft service journey with multiple paper boards. The participants expanded on the contents, completing steps, and filling out blank spots with a deck of cards depicting various elements of the service (touchpoints, actors, actions, places). The physical dimension (structural features) of the booth were also discussed, through role-playing and sketching activities. In the end, we asked participants to re-fill again the ‘intermezzo’ template, to gather their renewed impression of the automatic booth.

Figure 4: Co-design workshops, users and tools.

Benefitting from the results of the co-design workshops, we developed an exemplar version of the user journey and detailed ‘architectural’ requirements for the booth. The latter were then translated into a structure concept that took into consideration building complexity, forecasted cost (materials and construction), accessibility and aesthetics.

Phase 3: Prototyping

As already introduced in paragraph 1, to present the actual prototyping phase, this paper adopts as a basis the Service Prototyping Practical Framework proposed by Passera et al. (2012) and mainly refer to their terminology and definitions. We tackled Checkd. Through two levels of prototyping: as we followed a ‘zoom-out’ approach, we first prototyped one service moment only, i.e. the sample collection procedure. Second, as a progression, we prototyped the full-service experience.

Phase 3.1: Prototyping the sample collection procedure

Position in process and purpose

The co-design workshops produced an exemplar version of the Checkd. Customer journey.

We focused in particular on one service moment: the sample collection procedure (defined in this paper "procedure #1"), meaning the main sequence of interactions happening inside the booth when the user delivers their biological sample (eg. Sputum) to the machine.

Despite being in harmony with user needs and behaviours, it still sparked scepticism in the stakeholders, and it was deemed critical under an implementation point of view. The status of the technology running the PCR tests and its automation level, was, in fact, not advanced enough to implement the users' proposal, especially in a short time. It was, though, still considered as a valuable vision for future developments.

In a discussion with the startup two new procedures ("procedure #2 and #3"), both compatible with the current version of the technologies, were outlined.

Assumptions on possible pain points and problems the users could face were also identified. For example, procedure #2 was deemed the fastest and with less risk of contamination, while procedure #1 and #2 the most prone to user error.

What we did was carry out an evaluative prototyping session that included the three mentioned procedures. Why, to tackle the need of understanding which one to implement in the service-system. The 'How' will be described in the following paragraphs.

Author/resources

In this case the Author was responsible for both the prototype design and development and session management.

Here below the list of resources involved:

1. A 'service prototyping lab' solution was selected, since the servicescape was deemed not immediately fundamental to reach the prototyping goals.
2. Real users were involved, keeping as much diversity as possible, to address some specific hypothesis, mainly connected to older users. For example, actions in procedure #2 and #3 were judged too complex for this user category. 21 people were involved, aged 22 to 83 yeas old, from both business travellers and leisure travellers, with a balanced mix of both genders.
3. The 'staff' heuristic was not present, as Checkd. Can be categorized as a 'self-service' type of service (Blomkvist, 2011).
4. A mix of mock-ups and real props were used. Some devices that needed to be implemented did not exist yet (eg. Swab collection mechanism), so they were 'performed' by the Author; others were too difficult to get, due to time constraints, or were not crucial touchpoints (Passera et al., 2012). Other elements, instead, were real, meaning existing biomedical products.

Technique and process

As the sample collection procedure is a service moment that entails specific interactions, we decided to adopt the experience prototype technique. This approach, proposed originally by Buchenau & Suri (2000), “tries to replicate an existing situation or construct a new one, in which participants can understand, in an embodied way, what it feels like to interact with something” (Arvola et al., 2012, p.2). It aligns with the need of evaluating this peculiar service moment, which is not a singular contact with a touchpoint, but a mini-journey, a sequence of interactions with various interfaces and objects.

In the activity, the Author briefly introduced the meaning and purpose of prototyping, to then touch upon the general ‘booth’ concept, its link to Covid-19 and the number of procedures to be tested. Secondly, the procedures were simulated one after the other. Finally, an interview was carried out, starting with a very broad prompt question to allow ‘free speech’, to eventually pointing out specific questions, about steps’ details (safety, hygiene, instructions, comfortability).

Fidelity-resolution

The prototype resolution was medium-low and the fidelity of distinct aspects mixed. As proposed by Passera et Al. (2012) we developed a resolution graph, to frame the fidelity dimensions.

In the low-fidelity range we positioned the look and feel of the props and the technology, realism of the location: they did not directly impact the aspects that needed to be observed and therefore deemed less relevant. The functionality of the props and the technology, and the realism of the experience were medium fidelity. Implementing a good level of functionality, for both technology and props, was critical to guarantee the correct timing of the procedure.

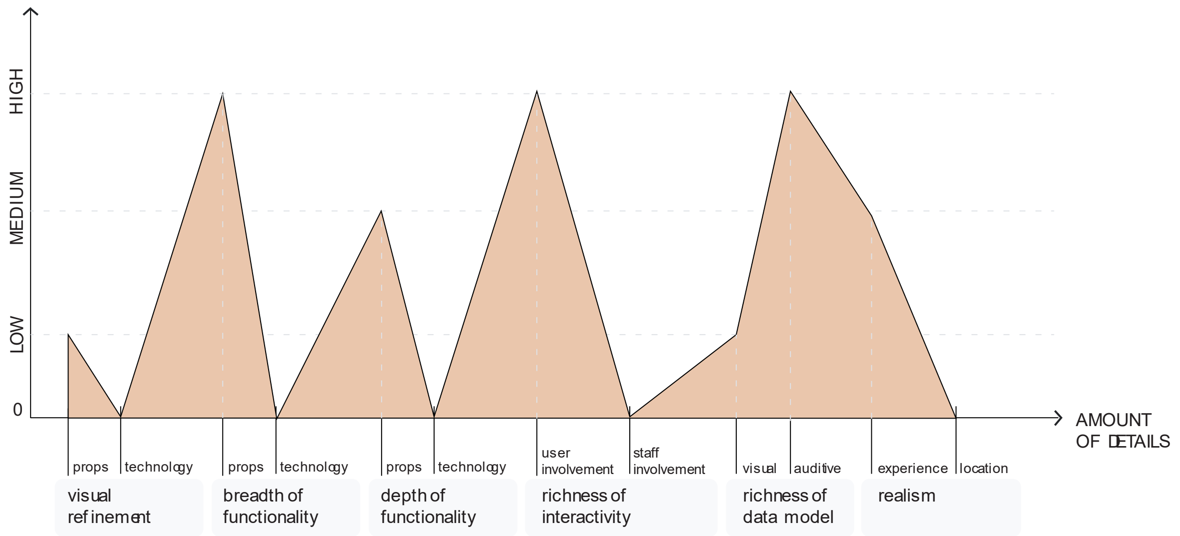


Figure 5 – The figure represents an adapted resolution graph regarding the prototyping the sample collection procedure.

We built the prototype set-up scene with cardboard panels and backstage elements (eg. Swab containers) with paper. Elements for procedure #2 and #3 were assembled from existing biomedical products (eg. Swabs and tubes, figure 6). For procedure #1, since the actual object did not exist, it was simulated using a marker (figure 7).

The Author, placed behind the panels, orchestrated the different elements, simulating the machine mechanics and giving instructions by voice (figure 8). No other video or audio support was given on purpose, so it was possible to understand the essential needs of the users on the matter.

Validity

Validity was limited in the sense that the setting hardly approximated the intended implementation context, despite only real users were involved. The servicescape, though, was not deemed a priority or for the goal of the prototyping moment.

Plausibility

Since the audience was kept into consideration while designing the prototype, as Blomkvist (2011) suggests, participants all provided very detailed and extensive feedback and engaged organically in explaining their own point of view.

Results

For each procedure, both quantitative and qualitative date were collected. On the quantitative side we gathered: total time of completion, completions with/without errors, number and type of errors. We considered 'errors' all the actions that deviated from the correct procedure steps (ex. Dropping swab, throw away wrong parts). Qualitative knowledge was gathered with open questions, regarding perceived hygiene, easiness of steps, physical comfortability.

We reviewed each session, as all of them were video recorded and noted following: procedure start and end (time), happening of errors, comments from participant, facial/physical reaction/behaviour, answers of final interview.

Insights were extrapolated from the gathered data by comparing the three procedures' completion times and number of errors, but also recognizing recurring errors and their causes.

Figure 6: On the left elements used and re-assembled during procedure #2 (tube, saliva funnel, preservation solution). On the right the element used for procedure #3 (lolliswab).

Figure 7: The tool used in procedure #1 to simulate a swab having the same concept of a marker, the red tape signaled a “no-touch” zone.

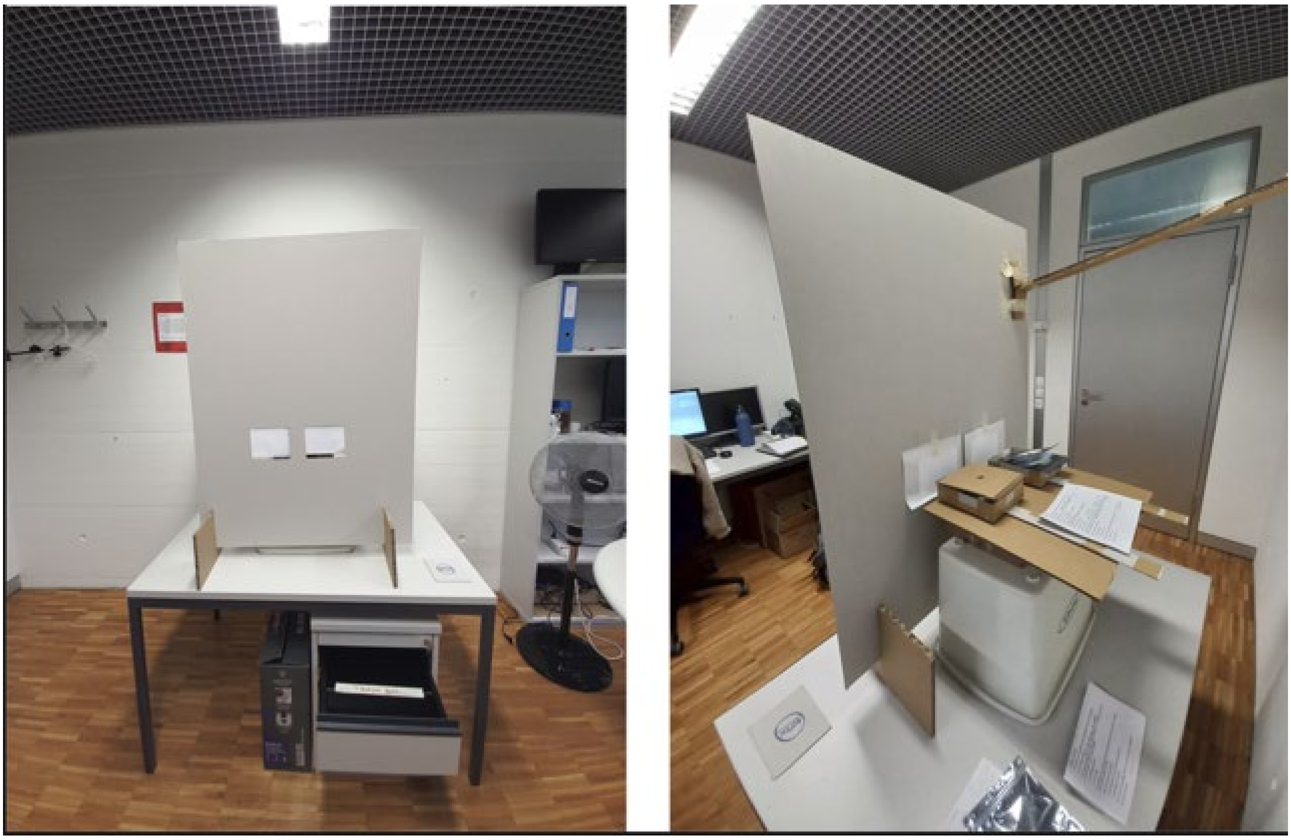


Figure 8: The set-up put in place for procedure #2, both front-stage and backstage.

Figure 9: User during the experience prototype of procedure #2 and the Author orchestrating the backstage.

Figure 10: Users during the experience prototype of procedure #1 and the Author orchestrating the backstage.

Phase 3.2: Prototyping the full-service experience

Position in process and purpose

The insights from the prototyping sessions just described allowed to select one procedure as the most fitting: it was procedure #3, as it demonstrated to be the most intuitive for the user and the most feasible form a technology perspective (it entailed relatively simple automation).

As this service moment was now defined, what we did after was a progressive step: prototype the full-service experience. This was fundamental to evaluate the experience from a holistic perspective, understand the effectiveness of the designed product-service system and get concrete recommendations to improve the Checkd. In its entirety.

Author/resources

The Author and the responsibilities were the same as the sample procedure prototype.

Here below the list of resources involved:

1. In this case, the location is ambiguous. Since Checkd. Can be defined a 'location-oriented service' (Blomkvist, 2011), executing the session in a realistic context was necessary. Primary sites for Checkd. Are transportation hubs, which were not available. The session was held in a university building, which is an actual secondary-choice location for the Checkd. Booths. For scenario purposes, we applied modifications to the environment and mainly considered it as an airport, but during initial parts of the prototyping, that entailed the user being 'at home'.
2. Real users were involved. Due mostly to time constraints, hard-to-reach site and length of activities, we had to restrict the user categories and focus mostly on younger people, both for business and leisure travel, which were easily reachable available to collaborate. 14 people were involved, with a balanced mix of both genders, from 21 to 33 years old.
3. The 'staff' was not present, as Checkd. Can be categorized as a 'self-service' type of service (Blomkvist, 2011).
4. A mix of mock-ups and real props were used. Physical artefact included real objects (booth, computer, screens, suitcase, hand sanitizer, gloves, swabs) and mocked elements (mostly the automation system: trays, doors, which were not yet developed). Digital artefacts were: Checkd. Website wireframing, two booth interfaces (outside and inside), digital receipt (email), digital test results (email).

Figure 11: The saliva solution and the swab for sample collection created in a sterile environment and assembled with real biomedical products.

Figure 12: Mock-ups used to simulate the automation system of the swab trays: on the left elements before assembling, on the right same elements in the prototyping setting.

Figure 13: The Checkd. Booth 1:1 scale prototype. In order: front and back, zoom on front (check in interface, doors, information panel), interior left wall (hand sanitization, saliva generation slot), interior centre wall (signage, procedure interface, sample slots), interior right wall (luggage area).

Technique and process

In this case the idea was to prototype the full-service experience: we adopted the Service Walkthrough technique, as it allows to represent the ideal service journey “in an embodied and holistic way” (Blomkvist & Bode, 2012, p.1).

Starting from the ideal customer journey, we selected critical service moments that could enact the most basic scenario, with the rule of having at least one from the three main service encounters (pre, during and post service), to then create all the artifacts and props necessary to give life to the ‘surrogate’ (Blomkvist, 2014) and find ways to coherently and smoothly orchestrate all the mise-en-scène.

All the activities were carried out the same day, while the sessions themselves were scheduled along a full week. The participants were first introduced to the practice of service prototyping, followed by the proposal of a set scenario (Covid-19 certification needed for a travel) and establishment of three main goals (with the main one of obtaining the fit to fly certification): understand what the service is about/how it works; book a test appointment; go to the appointment. We provided the users with a laptop and an interactive, but wireframe-level version of the Checkd. Website, where they started the roleplay exploring the website.

They continued going through the registration procedure, in which they had to deal with multiple document mock-ups and spend time typing in real information, to then carry out the booking procedure. After they received their personalized booking confirmation (programmed email sent by the Author during the prototyping session) the Author would ‘push’ the scenario forward in time, at the day of the booking and invite the user to autonomously reach the location, by following the instructions on the email, also providing contextual props (suitcase, bags, phone).

Different wayfinding elements were placed along the way to guide the user. Once reached the location the participants would ‘check-in’ at the booth, go through the full swabbing procedure and receive, on the spot, another personalized email with their fit-to-fly certification.

Finally, we carried out an interview, by initially asking a very broad prompt question to allow free speech, to eventually pointing out specific questions, about the different aspects of the experience.

At the end of the interview some brand identity elements related to Checkd. (logo and palette) were ‘parallel prototyped’, with participants invited to provide their feedback.

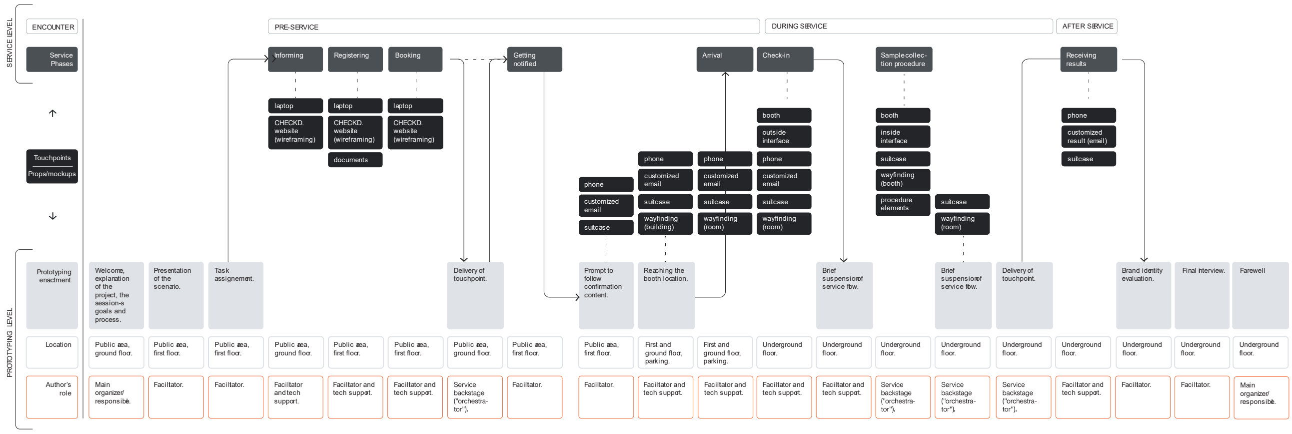


Figure 14: Diagram of the service walkthrough: on the top part (service level) are represented the service steps selected for the prototyping, while in the bottom part (prototyping level) the parallel breakdown of activities, locations and Author's role.

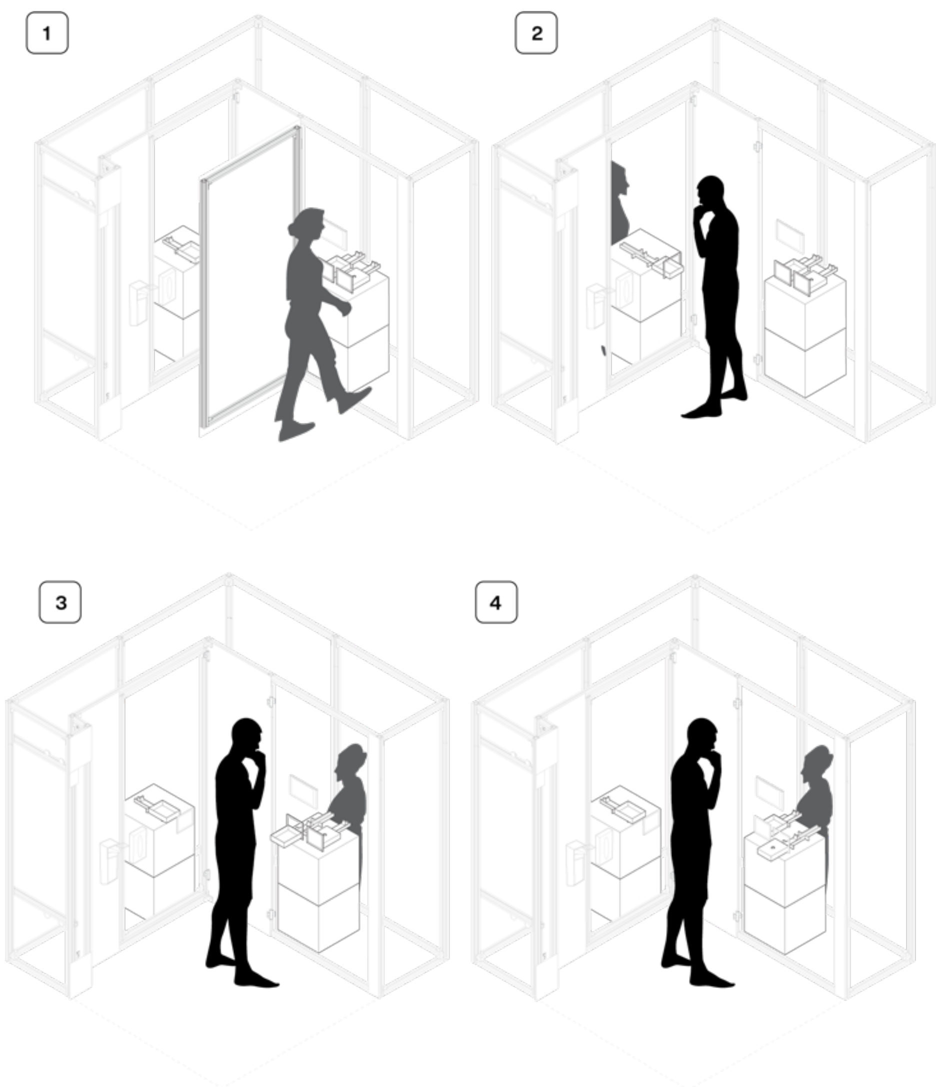


Figure 15: Axonometric view that shows the sample collection procedure moment and the relationship between author (gray), structure (prop) and user (black).

Fidelity-resolution

The prototype resolution was medium-high with the fidelity of distinct aspects mixed. We positioned at the medium-low level the look and feel of the technology and the realism of the experience. Medium-high fidelity was kept for the props functionality and look and feel, along with the technology's functionality and realism of the location. In the case of Checkd. The servicescape and its elements – ambient conditions, spatial layout and function, sign, symbols and artefacts (Bitner, 1992) – were extremely important, as they had a high degree of influence on the users, their feelings, their understanding of the service and their interaction with the touchpoints.

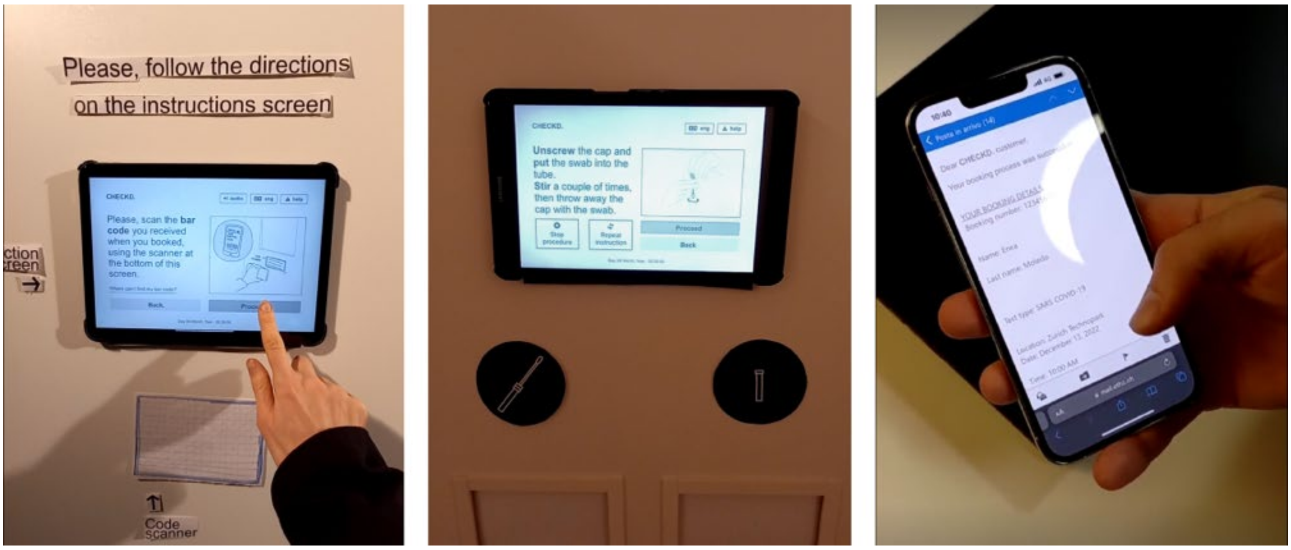


Figure 16: Some of the digital artefacts employed during the prototyping: look and feel were low fidelity, while depth and breadth of information and functionality were of higher fidelity.

Validity

Despite the larger context and location surrounding the prototype were similar to the implementation ones, aspects of the servicescape and other influencing factors could be replicated only in a limited manner. Moreover, it was taken into consideration that, although real potential customers were involved, they only represented a few user categories, and gave feedback only from their perspective.

Plausibility

Since the audience was kept into consideration while designing the prototype, as Blomkvist (2011) suggests, the participants all provided very detailed and extensive feedback and engaged organically in explaining their own point of view.

Results

Both quantitative and qualitative date were collected. On the quantitative side we collected information about time (browsing, registering, booking, check in, sample collection) and errors (presence and number). Qualitative knowledge was gathered with open questions regarding the overall service-system, the single service moments and their experience (pre, during, post service) and single elements (digital interfaces, structure/architecture, wayfinding/signage and their dimensions – functionality, data/information, interactivity).

The data were analysed in the following way: for each participant a customer journey map of the prototyped experience was made. While reviewing each session (all of them were video recorded) we noted in the different service phases the following data: start and end of task (time), issues, comments (positive, negative, …), facial/physical reaction/behaviour (surprised, annoyed, confused, …). These points were integrated with the answers of the final interview. Recurring comments and points of criticality were finally outlined and discussed with the stakeholders. Finally, a list of future improvements was elaborated.

Reflections and conclusions: towards a culture of (service) prototyping

The employment of the experience prototyping and service walkthrough techniques and the application the Service Prototyping Practical Framework (Passera et al., 2012) for the prototyping of Checkd. Produced some reflections, that we present here summarized in in the form of three main takeaways.

One first takeaway relates to the relationship between purpose and fidelity level. In both prototyping phases the low resolution and their related mixed fidelity did not hinder the right execution of the procedures and their correct evaluation. The opposite: low fidelity elements helped in leaving space for user interpretation and exploration.

A missing physical element or functionality, in fact, sparked more comments than a working/existing one. Participants proactively engaged with the prototypes and their elements, 'showing' their perspective (eg. What they would do differently, new ideas) rather than only 'telling'. They used props or role-played situations. Only occasionally participants were prompted, for example, with the question 'what do you think it is supposed to happen when you (…)?'.

It is interesting to highlight that prototypes that were mainly thought with an 'evaluation' purpose naturally shifted towards being more 'explorative', due to the fidelity level of the prototypes themselves. This led to a more participatory design dimension, highlighting the need of carrying out additional co-design activities about some specific service moments and touchpoints. We may argue that in this case the boundaries between co-design and prototyping were blurred, as we continuously 'moved' between testing activities and re-designing them with the help of the users-participants.

Another aspect that supported this prototyping-purpose transformation was adopting a technique of usability testing, the 'think aloud' protocol, where the user voices what they are doing, thinking or feeling while solving a task or a problem (Someren et al., 1994). Applied to both experience prototyping and service walkthrough, it gave the ability to participants to be more comfortable and empowered in externalizing their own views.

A second takeaway concerns iterations of service walkthroughs and servicescapes. With Checkd. The test situation corresponded to the real implementation context only in certain aspects (mainly superficial and related to the 'look and feel'). Many other different factors that usually shape the original servicescape (eg. Airport) were not implemented, despite being highly influential on the service experience and the customer successfully reach their goal.

From this point emerges the necessity of iteration. Multiple progressive sessions would allow to increase each time the level of fidelity and validity.

For example, in the case of Checkd. It would be interesting to do more service walkthroughs, each time adding more variables (eg. Waiting time, random errors and failures, ambient sounds or more user categories do the walkthrough simultaneously, implementing the trays automation system) that raise the level of realism. In any case, despite the number of repetitions, we experienced (by ourselves) that it is vital to prototype as soon as possible to advance in the project (Blomkvist et al., 2012), even if the fidelity level is very low. It is better to test some crucial service moments and, if needed, come back and co/re-design them, to then test them again. The continuous flow between co-design and prototyping that we mentioned before should be adopted.

Finally, a third takeaway relates to the role of the Author. Passera et al. (2012) and Blomkvist (2011) provide similar descriptions about the Author and identify he/she as the person in charge of designing the service prototype and taking decisions regarding the alternatives.

During the prototyping phase of Checkd., the Author performed many roles: she was at times creator (session design/planning), at others facilitator (supporting/following users) or orchestrator (performing backstage actions). This metamorphic nature is essential in medium-low fidelity prototypes, where the Author intervention is required to make the service mechanisms work. We believe that here there is room for further research: it is important to educate and prepare the Author in playing different roles and jumping between them, seamlessly. The multiple role situation can, in fact, hinder the prototyping activities when sessions are long and services simulated have many different dimensions. Complications in recording, frequent interruptions of service flow and incorrect execution of actions can happen or user comments/behaviours can go unnoticed. In these cases, the presence of multiple ‘Authors’, taking up different roles could benefit the research, as each person can focus on one or a few roles, always though collaborating with the others. This means to educate and create a prototyping group of Authors, able to intervene at any stage, especially in complex and articulated projects as services are in most of the cases.

Such perspective is strictly connected to what McElroy (2017) suggests at the beginning of her book: it is fundamental not only to prototype and have a personal mindset toward prototyping, but above all to develop and spread an actual culture of prototyping. This is even more important in the service design discipline, in which the combination of tangible and intangible elements creates a great complexity and generates the need of setting a constant feedback and user testing loop. In this context, the Author is not only a facilitator and an orchestrator of the prototyping process, but he/she should also become advocate of a broader prototyping culture that allows to better advocate the user within its organisation, who should be always placed at the centre of any (service) design actions.

References

Arvola, M., Blomkvist, J., Holmlid, S., & Pezone, G. (2012). A Service Walkthrough in Astrid Lindgren's Footsteps. In Proceedings of Service design and innovation conference ServDes 2012. Espoo, Finland: Linköping University Electronic Press.

Bitner, M. J. (1992). Servicescapes: The Impact of Physical Surroundings on Customers and Employees. Journal of Marketing, 56(2), 57–71.

Blomkvist, J. (2011). Conceptualising Prototypes in Service Design. Linköping University Electronic Press.

Blomkvist, J. (2014). Representing Future Situations of Service: Prototyping in Service Design. Linköping University Electronic Press.

Blomkvist, J., Åberg, J., & Holmlid, S. (2012). Service walkthroughs to support service development. In Proceedings of Service design and innovation conference ServDes 2012. Espoo, Finland: Linköping University Electronic Press.

Blomkvist, J., & Arvola, M. (2014, September 1). Pausing or not? Examining the Service Walkthrough Technique. In Proceedings of the 28th International BCS Human Computer Interaction Conference. Southport: UK.

Blomkvist, J., & Bode, A. (2012). Using Service Walkthroughs to Co-Create Whole Service Experiences. In Proceedings of ISIDC 2012 National Cheng Kung University. Tainan:Taiwan.

Buchenau, M., & Suri, J. F. (2000). Experience prototyping. In Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, 424–433.

Budde, R., Kautz, K., Kuhlenkamp, K. and Züllighoven, H. (1992), "What is prototyping?", Information Technology & People, Vol. 6 No. 2/3, pp. 89-95.

Floyd, C. (1984). A Systematic Look at Prototyping. In: Budde, R., Kuhlenkamp, K., Mathiassen, L., Züllighoven, H. (eds) Approaches to Prototyping. Springer, Berlin, Heidelberg.

Kammersgaard, J. (1983). A Discussion of Prototyping within a Conceptual Framework. DAIMI Report Series, 12(169).

Kelley, T. (2001). Prototyping is the shorthand of Design. Design Management Journal, 12(3), 35- 42.

McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., & Vera, A. (2006). Breaking the Fidelity Barrier: An Examination of our Current Characterization of Prototypes and an Examples of a Mixed-Fidelity Success. In Proceedings of CHI 2006. Montréal, Canada: ACM.

McElroy, K. (2016). Prototyping for Physical and Digital Products. O'Reilly.

McElroy, K. (2017). Prototyping for Designers. O'Reilly.

Passera, S., Kärkkäinen, H., & Maila, R. (2012). When, how, why prototyping? A practical framework for service development. In Proceedings of XXIII ISPIM Conference. Barcelona: Spain.

Sanders, E.B.N. and Stappers P. J. (2014). Probes, toolkits andprototypes: three approaches *to making in codesigning, CoDesign: International Journal of CoCreation in Design and the Arts, 10:1, 5-14.*

Someren, M. W. van, Barnard, Y. F., & Sandberg, J. A. (1994). The think aloud method: A practical guide to modelling cognitive processes. Academic Press.

Zomerdijk, L. G., & Voss, C. A. (2010). Service Design for Experience-Centric Services. Journal of Service Research, 13(1), 67–82.

Daniela Selloni
Daniela Selloni is Assistant Professor at the School of Design – Politecnico di Milano. She works on service design and social innovation, more specifically her research focuses on methods and tools of co-design and how collaboration can be experimented in public and private organizations.
She is a member of POLIMI DESIS Lab (part of the Design Department of Politecnico di Milano and founder of the international network DESIS, Design for Social Innovation and Sustainability) with which she has worked on numerous Italian and international research projects, dealing with design for local development, place making, sharing economy, public services and urban commons.

Serena Stefanoni
Serena Stefanoni is graduated in Product-Service System Design at the School of Design of Politecnico di Milano, who holds a background in Interior Design. She spent a semester as an exchange student in the Department of Chemistry and Applied Biosciences at ETH Zürich and as an intern at Diaxxo AG, a biotech startup, where she worked as the sole Service Designer in a multidisciplinary team on diagnostic devices. Currently she focuses on bringing a human-centred service design view to a more engineering-driven world.

Track 3: Research processes and methods 1

– The Phenomenon of Low-Fidelity Prototyping – An Overview Across Design Practices Making Deliberately Simpler Models

– Cultivating and Eliciting Felt Experiences for Design Use: Physical Manifestations of Abstract Bodily Experiences

– Creating translational knowledge: the role of visual communication design and prototyping methods in the research process

– Prototyping an employee experience model. A participatory action research project to support organizations in redefining the working routines starting from Employee Experience Design

The Phenomenon of Low-Fidelity Prototyping – An Overview Across Design Practices Making Deliberately Simpler Models

Rolf Brändle,
Folkwang University of the Arts, Germany;
Bauhaus University Weimar, Germany
Paula L. Schuster,
Humboldt University Berlin, Germany;
University of Applied Sciences Potsdam, Germany

Abstract

The phenomenon of low-fidelity prototyping is mainly discussed in HCI but is practiced in product design, architecture and speculative design as well under different terms. In this paper, we provide an overview of the disciplinary low-fidelity prototyping practices and discuss the overarching discourses among these fields.

Starting with an expanded understanding of prototypes as tangible and concrete models we investigate the tactic of designing a deliberately simpler models for different purposes. Prototyping with simple means with high abstraction poses challenges. Yet, the lack of reflection of a low-fidelity tactic holds unexplored potential. We investigate whether it is advantageous to prototype with a lower fidelity, even if a higher degree of fidelity is possible during the design process.

We present four discourses to explore low-fidelity prototypes: First, the concept of fidelity is discussed as well as whether fidelity and dimensions are a matter of interpretation. Second, the effect of open prototypes on communication among the involved people is explored. Framing low-fidelity as open, ambiguous, abstract and fuzzy highlights its communicative qualities. Third, low-fidelity prototyping beyond linear processes as well as the representation paradigm are scrutinized. Fourth, questions regarding limited skills and limiting materials, covering material choice and the application of toolkits, are addressed.

Overall, we investigate which design skills are needed for low-fidelity prototyping, as we claim that designing with low-fidelity implies as many design decisions as with high-fidelity.

We aim for a better theoretical foundation and reflection of low-fidelity prototyping that is needed for design education and the exchange among different design fields across terminological boundaries. This is the basis on which to discuss the role of designers and design researchers and how they use their low-fidelity prototyping skills for knowledge production in transdisciplinary research.

Prototyping, Low-Fidelity, Model Making, Abstraction, Ambiguity

How can something incomplete and imperfect be better than something complete and perfect? Low-fidelity (lo-fi) prototypes are a paradox, more specific and concrete than words due to their materiality, but vague and ambiguous in their partly undesigned form. It can be seen as "counterintuitive" (McCurdy et al., 2006) that simple prototypes with lo-fi can provide the most valuable insights. Prototyping is gaining new attention as a fundamental design practice. We assume that lo-fi prototyping is a common phenomenon in many design fields, 186uti s unequally labeled and discussed under different terms.

The term lo-fi prototyping emerged in human-computer interaction (HCI) and is up-to-date; mostly discussed in HCI-related design research. To advance the discourse on fidelity in design, we expand the discourse by exploring the lo-fi phenomenon across multiple design fields. We will therefore shortly explain various concepts of lo-fi prototyping and their respective synonyms in the design fields of HCI, architecture, product and industrial design, as well as critical and speculative design based on a literature review.

Through an iterative clustering approach, we derive four discourses about low-fidelity, following specific criteria for their relevance for design research. Our thesis, that lo-fi prototyping, even if named differently, occurs in the different design areas, shall show which similarities exist, but also where differences exist. This should help design researchers make conscious decisions regarding the fidelity of prototypes for different purposes. We aim at exploring the prototyping skills necessary for designing prototypes adequately and explore the tactic of using a deliberately simpler way.

Before we start, we need to define two key terms in the form of an experimental preunderstanding (Wendler, 2013), to enable a discussion beyond terminological boundaries.

Prototypes and Prototyping

Scholars stay vague when defining prototypes (Dickel, 2019; Gengnagel et al., 2015) because of their flexible and heterogeneous nature. We still observe, as Houde and Hill (1997) stated, that different design disciplines have different notions of prototyping and different expectations of prototypes.

There are a few works that look at prototypes in a general way and across the boundaries of different design fields (Adenauer & Petruschat, 2012; Buchenau & Suri, 2000; Camere & Bordegoni, 2016; Exner et al., 2015; Lim et al., 2008). In addition to these overviews originating from design itself, other works from STS (Science and Technology Studies), anthropology, and art history take a look at prototyping practices as well (Ewenstein & Whyte, 2010; Janda, 2018; Schrage, 1999; Wendler, 2013; Yaneva, 2013). Lo-fi prototyping is discussed as a practice that enables exploring several alternatives at once and many iterations along the process (Yang & Epstein, 2005). Kannabiran & Bødker (2020) emphasize, "different prototyping techniques enable different modes of inquiry with varied intentions and outcomes" and "allow us to ask different sets of questions". Regarding its purpose, the prototype takes on different roles in different situations for different audiences.

Prototypes are understood as "an incomplete portrayal of a design idea" (Lim et al., 2008), "physical manifestations of ideas or concepts" (Sanders & Stappers, 2014°), or "representations of a design made before final artifacts exist" (Buchenau & Suri, 2000). Other scholars like Adenauer and Petruschat (2012) show the processuality of prototypes and therefore prefer to speak of prototyping rather than prototypes.

> *In our expanded understanding, we regard prototypes as artifacts created in the design process. They are specific forms of tangible and concrete models serving various purposes.*

Fidelity and Low Fidelity Prototyping

The fidelity of prototypes is a specification that HCI practice and research traditionally uses. It is either described as the “precision of a prototype” (Beaudouin-Lafon & Mackay, 2007), the “level of realism” (Yang & Epstein, 2005), the “level of refinement or degree of detail displayed by a prototype“ (Blomkvist & Holmlid, 2011) or the “level of correspondence with the product-to-be, i.e. the quality of the representation that the prototype offers” (Camere & Bordegoni, 2016).

To approach a definition, the notion of the prototypes as a “filter” (Lim et al., 2008) is useful. As one of the central images to understand fidelity, the filtering of prototypes describes that some dimensions of the future product (such as form, function, experience, symbolism, needs, etc.) are filtered out in the prototype whereas others are manifested. The fidelity is often quantified in comparison. A lo-fi prototype has filtered out more dimensions compared to a hi-fi prototype.

Lo-Fi Prototyping appears under different terms in the design fields selected for this paper. Some are synonyms, others are specific examples of the phenomenon: quick and dirty prototyping, props, mockups, dummies, paper prototyping, throw-away prototyping, proportion models, wireframes, or assemblies.

> *We see lo-fi prototyping as a decision to intentionally use or even create ambiguity in artifacts to gain an advantage for the ongoing process even though a higher degree of fidelity would be possible.*

1. Overview

We explore the phenomenon of lo-fi prototyping across four design fields to provide an overview of the similarities but also the differences of prototyping practices.

Methodologically, we chose the fields of HCI, architecture, product design and speculative design based on the following criteria:

- They are among the fields with the most intensively practiced prototyping.
- They represent design study programs and have their own specialist conferences.
- They cover digital as well as physical artifacts in different scales.
- They cover opposing ends on the axis of applied versus artistic design practices, therefore serving different purposes of prototyping.

Regarding the question of which fields to include and exclude, we considered participatory design as a relevant practice, yet more as a methodology, and therefore decided to include it in the fields of their respective design outcomes.

1.1 Human-Computer Interaction (HCI)

The concept of the fidelity of prototypes is rooted in HCI. Common synonyms for lo-fi prototypes are “mockups [or] paper prototypes” (Beaudouin-Lafon & Mackay, 2007) (see Figure 1), “wireframes” (McCurdy et al., 2006), “low-tech prototypes” (Barati et al., 2019), or simply “artifacts” (Flechtner et al., 2020). Following a technical and pragmatic approach, low-fidelity prototyping is a “matter of cost” (Lim et al., 2008) and is associated with “quick and dirty” (Coughlan et al. 2007).

Often, fidelity is linked to the degree of interactivity in HCI (Rudd et al., 1996), and technical functions are simulated as such in “wizard of oz prototypes” (Beaudouin-Lafon & Mackay, 2007).

Figure 1 Paper prototype of a food sharing app by Schmitz, design course taught by Schuster, FH Potsdam (2017)

The central image Lim et al. (2008) use to describe the prototype-product relation is the prototype as a “filter”. “The designer screens out unnecessary aspects of the design so that they can extract knowledge about specific aspects [...] more precisely and effectively.” (Lim et al., 2008). Wong (1992) describes “rough and ready prototypes” where issues not for discussion are represented in a low-resolution form and thus allow to focus on one question. An increased fidelity does not result in increased insight (Diefenbach et al., 2013). Surpassing the well-discussed evaluating role of prototypes, Lim et al. (2008) argue for a diversification of their roles towards “evolutionarily learn, discover, generate, and refine designs” with prototyping.

With service design growing as a field, the use of design methods has increased (Blomkvist & Holmlid, 2011). Lo-fi prototyping is embedded in structured design methods in Human-centered-design and influenced by Design Thinking. When designing complex systems, prototypes not only manifest physical or digital artifacts. They expand to processes, interactions and experiences. The “experience prototype” (Buchenau & Suri, 2000) includes “body storming” (Oulasvirta et al., 2003), incorporating the body in form of role-play into the lo-fi prototype (see Figure 2).

Figure 2 Lo-Fi prototype of a wearable soft robotics orthosis from a participatory workshop using body storming, project: PowerGrasp (Flechtner et al. 2020)

Lo-Fi is often used with toolkits as a participatory design strategy to include people from non-design backgrounds without technical skills. Khan & Matthews (2019) use a “constructive assembly” as a toolkit: a reconfigurable, modular physical set of basic materials. Following the authors, the assembly ensures to "never start from nowhere". Imperfect low-fidelity is a fundamental tactic since perfection and hyper realism are impossible to achieve (Khan & Matthews, 2019)

1.2 Architecture

While the term lo-fi prototyping is not common in architecture and "models" are more common, the tactic of voluntarily simpler models has long been in practice. A well-described example is the models used for the construction of St. Peter's Cathedral in the 16th century (Lepik, 1995). In opposition to his predecessor, Michelangelo denounced the "fetishistic" obsession with detail in Sangallo's model, since the constant increase in fidelity meant that the scope for action was lost (Bredekamp, 2008). Michelangelo's simplified models (see Figure 3) allowed for a more organic building process and, as Bredekamp (2008) outlines this "minor forma", emphasized his superior artistic judgment.

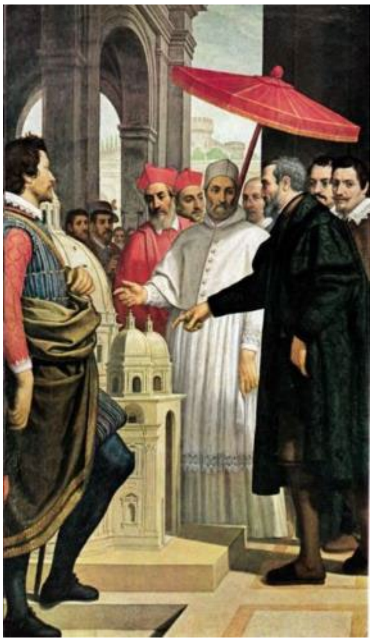


Figure 3 Michelangelo showing his model. Painting by Passignano (1618/1619)

Recent architectural scholars have addressed low-fidelity in two ways: a deliberate choice of simple materials to enable the exploration of spatial issues through the materials´ ambiguity and resistance (Cannaerts, 2009, Henderson, 2016), as well as a necessary abstraction to represent a building on a smaller scale and focus on its essentials (Yaneva, 2005).

The limiting factor of materials in model making has often been highlighted as problematic, see Rittel (1973) who calls the model itself a wicked problem, or Benisch who claims that toy bricks can only create toy-brick architecture (Benisch in Wendler, 2013). Analog models made of cardboard, foam, or wood are used to quickly and inexpensively clarify spatial questions and to gather initial impressions (see Figure 4). These can be seen as a supplement to sketches, axonometrics, or CAD drawings and allow for quick collaborative design (Ammon, 2013).

More recent studies show models that go beyond these traditional materials. For instance, Bernhardt shows how the ideas of the people involved can be strengthened through the clever choice of the simplest materials, like foldable vegetable crates (see Figure 5), pebbles, or blankets, thus facilitating participation(Bernhardt, 2016).

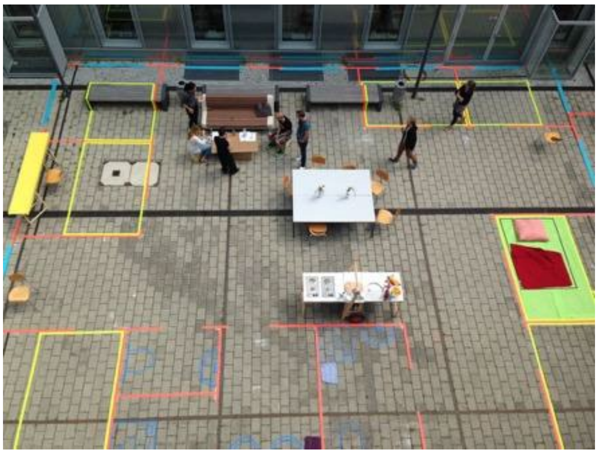


Figure 4, left - Participatory Project for Student Apartments by Martini, Brändle and Maroke, project: Eckwerken, FH Potsdam. (2014)

Figure 5, right - Workshop with foldable vegetable crates by Bernhardt, BeL & urban catalyst studio, project: Gärtnerhof Overmeyer Organic Farm, Seevetal. (2014)

Yaneva (2005) describes the oscillating between scaling up and scaling down. Scaling down refers to a voluntary smaller-scale model to “evoke things and make broader assumptions”, while their larger counterparts visualize sizes, shapes and precise positions (Yaneva, 2005).

1.3 Product and Industrial Design

According to the typology of models in traditional industrial design by Busse (Busse in Adenauer & Petruschat, 2012), several types of models can be considered low-fidelity. Particularly, these are early-used models such as proportion models or functional models that serve the development process. In these processes, the fidelity increases from model to model and only the final model is called a prototype. In the English-speaking world, the term prototype is also used earlier in the process, mostly known as quick and dirty prototyping. Mockups are used in a similar way to architecture, as props for presentations. Derived from the French term “maquette”, meaning unfinished draft or sketch (Colonnese, 2016), mockups are imitations that, depending on their execution, can be quick dummies or demonstration models with a greater degree of detail. It seems to be common knowledge among product designers that an overly finished representation can block productive critique of a design.

Two current developments favor the low-fidelity character of the prototypes.

Firstly, the shift from processes where products are planned according to an initial specification list, to processes in which early models are used to find new requirements in the first place (Sanders and Stappers,2014b). The advantage of lo-fi prototypes is, therefore, that their unfinished nature can be seen as an openness to other stakeholders.

Secondly, the process that leads to a product plays a much greater role today. The process itself becomes part of communication (Frye, 2017). Featured Making-Ofs by author-designers emphasize the organic process of designing a product and thus show early unfinished models that used to be hidden (see Figure 6+7). This can even lead to low-fidelity deliberately ending up as a stylistic device in finished products (see Figure 8), as Frye shows through the work of van Eijk (Frye, 2017).

Figure 6 Gricic, Paper Models for the Krups kitchen appliances project. Prominently shown on Gricic's Website. (2005)
Figure 7 Model process by the Bouroullec brothers, featured in a workplaces Story by friends of friends, Photograph: Chéné (2016)
Figure 8 van Eijk's Floating Frames Sculptures (2010-2013)

1.4 Critical and Speculative Design

In contrast to the previous three design fields, the focus of speculative design is on debate and provocation, rather than on products to be invented and manufactured (Dunne & Raby, 2013). A permanent increase in fidelity is not necessary per se. Objects of design fiction are "props for nonexistent films"(Dunne & Raby, 2013) or so-called "diegetic prototypes" (Kirby, 2010). Lo-fi prototyping, therefore, shows itself in two ways. A carefully crafted abstraction and the use of models to quickly visualize futures with participants.

Dunne and Raby (2013) describe Aesthetics of the Unreal as a visual language that can simultaneously represent the real and the unreal. The approach of addressing an audience through ambiguity, and thus promoting multiple perspectives, seems to be a respected effect of this aesthetic (Dunne & Raby, 2013; Gaver et al., 2003). Speculative objects, in this sense, are prototypes of futures. Whereas a high level of refinement is commonly used to simulate a real scenario, the tactic of low-fidelity is used as well and discussed less. Abstract prototypes consciously avoid a too-high realism through skillfully crafted ambiguity to protect themselves from criticism of feasibility and to create spaces for interpretation (Dunne & Raby, 2013). The "reduced physical design languages devoid of details" (Dunne & Raby, 2013) of these prototypes and their deliberately chosen model aesthetics can be considered low-fidelity (see Figure 9).

Figure 9 Prototypes of smart objects in a film, showing abstraction through monochromatic design, project: Uninvited Guests, by Superflux (2015)

Aside from these artifacts used mostly in exhibitions, speculative designers use lo-fi prototyping for participation (Bardzell & Bardzell, 2013). Here, the low-fidelity is apparent in the easy-to-process inclusive materials that participants can use to quickly make their visions tangible (see Figure 10). It is about the process of designing artifacts rather than interacting with finished – but intentionally unfinished-looking – artifacts. This speculation, through the making of rapid visual and physical prototypes, not only stimulates the imagination of participants but can also expose deeper personal desires or fears (Andersen & Wakkary, 2019; Tost et al., 2022).

Figure 10 Participatory lo-fi prototyping in a lab setting with a range of accessible materials, project: sense objects, by Extrapolation Factory (2018) (left); Lo-fi prototype created in a participatory workshop in the project: pawn tomorrow, by Extrapolation Factory (2014) (right)

2. Discourses

Based on the literature review of the prototyping practices in the four design fields, several discourses emerged. Through iterative clustering, we derived four main discourses that are relevant for design research, along these criteria:

- Brings forward the prototyping discourse and scrutinizes the rigid central concepts of fidelity, dimensions, the representation paradigm and linear evolution
- Covers several design fields to provide an interdisciplinary point of view
- Is relevant for further exploration in design research, such as open-ended artifacts and processes, and tackling complex challenges

- Grasps the prototype as a medium as well as a material, and includes the prototyper's perspective

2.1 Fidelity and Dimensions are an Interpretation

The "high-vs-low-fidelity-debate" in HCI revolved around the question of whether a low, a high, or a medium fidelity is appropriate for a prototype, by contrasting their advantages and disadvantages (Houde & Hill, 1997; McCurdy et al., 2006; Rudd et al., 1996; Wong, 1992; Yang & Epstein, 2005). To advance the discourse we concentrate on the applicability of the concept of fidelity.

HCI divides the phenomenon into much smaller parts than the other disciplines. Lim et al. (2008) distinguish the "scope" and the "resolution"of a prototype corresponding to "the breadth and the depth in fidelity" (McCurdy et al., 2006). The problem with a binary distinction between low and high-fidelity is also discussed (Lim et al., 2008). Occurring "mixed fidelity" is emphasized to describe that fidelity is high in some dimensions and low in others (McCurdy et al., 2006).

The challenge of deciding on the right dimensions to direct the focus lies in "fidelity trade-offs" (Barati et al., 2019), e.g. using visual qualities versus performative qualities. This decision which dimensions are favored is frequently informed by routines and accessible tools, rather than an actual reflection (Diefenbach et al., 2013). To deal with the limited scope and purpose of a specific prototype, Barati et al. (2019) propose the combination of several prototypes to depict different dimensions. Which dimensions are manifested as low- or high-fidelity is therefore also a question of the designers' skills of abstraction, how they assess the audience's ability to read the prototype (Blomkvist & Holmlid, 2011), the "transfer to product" (Buchenau & Suri, 2000), and precise communication of which dimensions are not addressed by a prototype (Houde & Hill, 1997). A vague lo-fi prototype needs even more framing than prototypes of higher fidelity.

In model theory, Wendler (2016) emphasizes that the identity of a thing as a model is a consequence of people perceiving the thing as a model. Whether a sketch or a "brick" (Houde & Hill, 1997) is a prototype depends on whether or not it is agreed on. This perceptual dependence applies to its fidelity as well. Lo-fi prototypes have a "low perceived finishedness" (McGrath et al., 2016), yet fidelity is not an objective property of an artifact that is clearly readable by its appearance, but as an interpretation depending on the context. Materials, aesthetics and shape give hints in regard to seeing traditions, e.g. of a frequently used paper, card, foam core (Coughlan et al., 2007) as prototyping material. Similarly, wireframes in user interface design communicate a prototypical low-fidelity state by the black outlined boxes with system fonts. Yet, without an explanation about the future product, the fidelity is not clearly identifiable. Imagine a paper prototype for a paper product–the paper itself could seem low-fidelity but is high-fidelity in this example.

2.2 Openness Fosters Communication

Understanding lo-fi prototypes as open, abstract and fuzzy allows for new conclusions. Instead of limiting the understanding of low-fidelity to the notion of simplification and filtering, there is an enriching effect through the prototype's incompleteness. The higher the degree of abstraction, the more open the prototype becomes. Dickel (2017) describes the prototype as a medium that communicates since the message itself is a message (McLuhan, 1964). Low-fidelity communicates, therefore, that the artifact is only “a proposal–provisional and open to change” (Lim et al., 2008).

The fidelity of a prototype strongly influences whether a prototype is read as a template to be transferred or as an open basis for discussion (Buchenau & Suri, 2000; Rudd et al., 1996). As an interesting parallel, the authoritarian effect of Sangallo's model of St. Peter's seems to be the same as that of a frontend developer who uses the hi-fi prototype of a user interface as a design guide (Bredekamp, 2008; Rudd et al., 1996). The corresponding low-fidelity counterparts of these examples open up a communicative space which is the central purpose of low-fidelity (Bähr, 2012; Buchenau & Suri, 2000), especially communication “on high level issues” and concepts (Wong, 1992). Prototypes communicate to various stakeholders for various purposes, such as ideating or testing (Lim et al., 2008). Prototypes are also used to facilitate discussions (Sanders & Stappers, 2014a) or to argue for their plausibility (Dickel, 2019). Bähr (2012) describes how architects show sketches instead of renderings, since “a perfect model seems to be complete and somehow locked to suggestions”.

In research and participation focused as well as speculative design, the communicative purpose of lo-fi prototyping is even more central and diverse. On one hand, it is used as a consensus building strategy (Khan & Matthews, 2019) and to develop a shared vision (Kannabiran & Bødker, 2020). On the other hand, it is used to juxtapose multiple visions (Kannabiran & Bødker, 2020), to provoke, or as a “hyperstition” (Schmeer, 2019).

The openness of prototypes can lead to productive misunderstandings thanks to their ambiguity, as it gives rise to multiple interpretations (Gaver et al., 2003). Based on Star and Griesemer’s (1989) concept of “boundary objects”, Khan and Matthews (2019) regard “different disciplinary ‘readings’ of the artefacts” as “a feature” during participatory sessions. This is conceptually preceded by Eco’s (1989) notion of the “open work” which describes that authors can render modern artworks open to be further completed by the audience. The prototype has no static meaning inscribed but is constructed by interpretation. “The materiality of prototyping” brings forth “creative sites for the reinterpretation and ascription of meaning to constructions." (Khan & Matthews, 2019). Prototyping constructs the product as well (Adenauer & Petruschat, 2012) and low-fidelity makes this process more open-ended.

Concerning epistemic discourses, prototypes in the sense of “epistemic things” in experimental systems have a specific vagueness that incorporates what people do not know yet (Rheinberger, 1997). Epistemic things are unstable and a source of questions (Rheinberger, 1997). Knorr-Cetina (1998) sees epistemic things (“Wissensobjekte”) in contrast to mere instruments as “unfoldable” artifacts that can be opened and explored since they contain more possibilities. The prototype creates uncertainty about the “taken for granted” status quo, states Janda (2018), based on Dewey (1929). A low-fidelity amplifies the effect, as Oder (2020) also describes this tangible but vague character of models as a key aspect in knowledge-generating through design processes with the term "entwerferische Dinge".

Following these arguments, the low resolution of lo-fi prototyping is a tactic of using and producing fuzziness intentionally. This tactic of carefully crafted uncertainty embedded in artifacts gains more importance as design is increasingly used for research purposes.

2.3 Beyond linear processes

In many cases, lo-fi prototypes favor the earlier use of prototypes in the design process. (Camere & Bordegoni, 2016). This shift to prototyping earlier in the process comes along with increased embeddedness in ideation methods and use in exploratory spaces (Sanders & Stappers, 2014a) for “exploration-through-prototyping” (Camere & Bordegoni, 2016). The prototype is no longer seen only as an object, but as a performative practice (Suchman, 2002). Co-Prototyping has included new stakeholders (Kimpel, 2016) and “slow prototyping” is called for (Pfeffer, 2014). However, as the overview has shown, low-fidelity prototyping is not to be understood only as the initial counterpart to high-fidelity prototypes at the end. Fast iterations and saved material costs are desirable effects of lo-fi prototyping and not prerequisites.
Whether prototypes are considered “throw-away prototyping” and “evolutionary prototyping” is discussed in HCI (Bähr, 2012; Kordon & Luqi, 2002). Throw-away prototypes, mostly described as low-fidelity, are less complex to make so that the loss of the invested effort can be better tolerated. Contrasting this temporary use, evolutionary prototypes allow for future iterations. In HCI, this is often realized by choosing a medium close to the envisioned final product so that prototypes can be reprogrammed and iterated without starting over. Adenauer and Petruschat (2012) emphasize the cumulative effects of prototypes and show such evolutionary prototyping in other design fields too.

The demonstrative showcasing of the process with lo-fi prototypes, the mixed fidelity debate, a carefully crafted aesthetic of the unreal, or the repetitive scaling down, are all signs that low-fidelity can occur at any point in the process. This opens up the question of whether fidelity is a “linear increase within the process” (Beaudouin-Lafon & Mackay, 2007) and not rather a fundamental design tactic that keeps reappearing when applied to different dimensions. This non-linear understanding of prototyping reflects what is discussed in model theory as overcoming the representation paradigm. In classical model theory, each model is seen as a representation of an original (Stachowiak, 1973). Emerging simplifications are necessary factors of an objective representation relation (Stachowiak, 1973). From this view, the better a model can represent an original, the more it fulfills its purpose (Hertz, 1894; Wendler, 2013). By this way of thinking of the model as an objective reduction, only what is already known can be learned about the original (Knuuttila, 2011; Mahr, 2012; Wartofsky, 1979). Applied to prototyping in design, this means lo-fi prototyping is not a necessity where high-fidelity is not yet possible, but a deliberate choice. If we do not minorize models or prototypes as objective representations of the original or finished product, this opens up space for new insights.
Seeing something as low-fidelity is a practice on its own that evolves around the individual skills of the actors, the materiality, and media involved. The detachment of prototypes from their relation to a future product becomes especially relevant when no traditional products exist, like in speculative design. Moreover, it allows prototyping e.g. to address the needs and questions in research through design.

2.4 Limited skills and material as a limitation

Most lo-fi prototyping works with the simplest materials, such as paper, foam, wire, etc. The materials are quickly shaped and inexpensive. Nevertheless, lo-fi prototypes cannot be narrowed down along a boundary of the materials used, nor can they be defined by economic aspects alone. As Adenauer and Petruschat (2012) put it, these materials are good for “playing theater”. The materials are aesthetically exaggerated, sometimes even seen as craftsy or ordinary tinkering. This is obvious in the early stages of the project, but mockups or speculative objects show that, later in the process, prototypes are also made of materials that are meant to be more than they are. The ease with which a material can be deformed should not be confused with the degree of detail a material can display. The perceived fidelity of a material or technology can only be determined in relation to the actors involved and the specific context. There is a debate in HCI about the extent to which electronic or digital elements can be part of lo-fi prototyping (Barati et al., 2019), e.g., in the “blended prototyping” approach (Bähr, 2012) (see Figure 11).

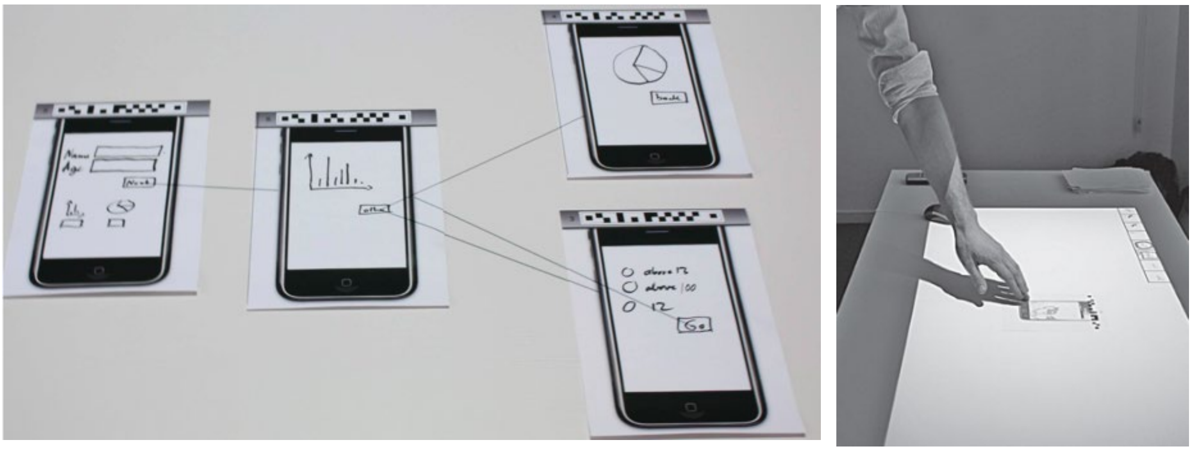


Figure 11 Blended prototyping is a tool to translate paper prototypes (left: Bähr et al., 2010) to experienceable click-dummies to foster quick iteration (right: Bähr, 2012)

That the limiting factor of the material is an advantage of lo-fi prototypes seems to be generally accepted (Tost et al., 2022; Frye, 2017). Khan and Matthews (2019) observed this in the context of participatory design: “The shape limitations forced participants to think of ways to share their ideas by relying only on rigid structures to help articulate their thoughts and ideas, and in doing so became more expressive”.

Since this limitation depends on the skills of the actors, the decision of which material to use for which purpose in prototyping plays a crucial role. Partly, material selection is the result of what is at hand in a situation, fostering improvisation (Frye, 2017) in the sense of a “bricolage” (Lévi-Strauss, 1973). In participatory workshop formats, someone else usually selects the raw or predefined materials, such as in “Lego Serious Play” (Khan & Matthews, 2019), for the participants, depending on their presumed skills. At the same time, companies have their standardized prototyping methods and hire people with appropriate skills.

Using lo-fi prototyping as toolkits (Sanders & Stappers, 2014a), (see Figure 12) and as methods brings both economic advantages and the belief in transparent and democratic processes. It is “a lever that lowers the barrier to participate” (Khan & Matthews, 2019). However, other scholars show that no process can ever be unbiased and equal for all (Mareis, 2016). It's the designer’s role to design and manage specific toolkits or shared spaces to enable others to co-create with their competencies (Sanders & Stappers, 2014b; Schrage, 1999). This expertise cannot be replaced by patterns alone and requires a high degree of “knowing-in-action” (Schön, 1984), “tacit knowing” (Polanyi, 1985), or "knowing how" (Ryle, 1945). Following Niedderer (2009), tacit knowledge and reflective practice with materials help to anticipate how artifacts can be used in a variety of ways to generate knowledge.

Figure 12 Toolkit of the hybrid participatory workshop "the other city 2" by Tost, Schuster, Flechtner, Budinger & Heidmann, project: PROTOTYP, FH Potsdam (2021) (left) and a resulting prototype showing a slow bus concept in a speculative city of the future by Thomet (right)

3. Conclusion

As we have shown, in many design practices the prototyping of deliberately simpler models is used to gain advantages. There is a consensus that this lo-fi prototyping is a valuable design skill. While the phenomenon of taking advantage of these simpler models has long been known, the debate concerning lo-fi prototyping is most extended in HCI. Nevertheless, HCI can learn from other traditions, just as these design fields can benefit from a transfer of the well-discussed concepts and designations in HCI. In addition to a terminological and conceptual discussion of fidelity, we are particularly interested in the implementation of fidelity in practice. Low-fidelity is more than just an attribute of prototypes and becomes a general design tactic. In these practices, the perceptual dependence of lo-fi prototypes and reframing low-fidelity as productive fuzziness and openness are essential perspectives.

Our key finding is that the prototyper's practices are at the heart of lo-fi prototyping. Lo-fi prototyping needs to be a reflective practice of carefully crafted ambiguity. Prototyping something consciously as low-fidelity is not easier than designing high-fidelity. Prototypers must be conscious of the effects of prototyping more openly or designing open prototyping formats for others. Due to perceptual dependence, this is particularly evident in the discourses around materiality and the necessary skills, as well as against the background of model theory.

With the focus on the prototypers, the emphasis is on their perception and their implicit and explicit knowledge. At the same time, as we have shown, lo-fi prototypes are mainly used in a knowledge-generating manner. This distills our overview down to knowledge questions. We, therefore, see prototyping, and lo-fi prototyping in particular, as an epistemic design practice.

As an outlook on the future of lo-fi prototyping and as further desiderata concerning this epistemic praxis, we see three interrelated challenges:

1. *Learning Low-Fidelity*
   How can lo-fi prototyping be taught in design education? We advocate that the indispensable practical experience of "knowing how" (Ryle, 1945) in materials is complemented by theoretical reflection on one's prototyping. Prototyping should be taught at every step of the design

process, and fidelity critically assessed by the teachers themselves. Students should develop the skill of designing the prototype with the right amount of abstraction appropriate for different purposes while ensuring minimal readability.

2. *Prototyping as an Epistemic Practice in Research Through Design*
How can the designerly epistemic practice of lo-fi prototyping be applied in research through design? Moreover, we ask about the role that designers can play in transdisciplinary research projects through these practices. How can collaborative research with other disciplines be conducted without substituting the designer's skills with standardized methods or marginalizing their tacit knowledge? When (co-) prototyping for knowledge production, material selection, an inclusive process, as well as facilitating fruitful discussions are part of research design decisions. For transdisciplinary research, transparent documentation and communication of the lo-fi prototyping practices are essential. Further research is required on how to craft the fuzzy parts of lo-fi prototypes as "epistemic things" to show what people do not know yet.

3. *A Sustainable Way of Lo-Fi Prototyping*
The problem with throwaway prototypes, apart from their material waste, is the untapped potential that these prototypes can play in an evolutionary understanding elsewhere in the process. To make prototypes accessible beyond their processes as a source of knowledge lacks a forum. While hi-fi prototypes sometimes find their way into exhibitions and archives, there is little wider dissemination for lo-fi prototypes. We would like to see the same access for modeling as primary sources as there is for natural science data sets and the original textual sources of the humanities, according to the claims of design as third knowledge culture (Archer, 1979; Cross, 2001). The lo-fi "prototypes as instruments of knowledge for research" (Kannabiran & Bødker, 2020) become an object of study regarding sociological questions of knowledge, as well. We, therefore, wonder what knowledge could be found if prototypes sustain for longer and were accessible beyond one's stakeholders and peers.

References

Adenauer, J., & Petruschat, J. (Eds.). (2012). *Prototype! Physical, virtual, hybrid, smart ; tackling new challenges in design and engineering*. Form + Zweck-Verlag, Berlin.

Ammon, S. (2013). Wie Architektur entsteht. Entwerfen als epistemische Praxis. In S. Ammon & E. M. Froschauer (Eds.), *Wissenschaft Entwerfen* (pp. 337–361). Wilhelm Fink Verlag, München. https://doi.org/10.30965/9783846755211_014

Andersen, K., & Wakkary, R. (2019). *The Magic Machine Workshops: Making Personal Design Knowledge* (p. 13). https://doi.org/10.1145/3290605.3300342

Archer, B. (1979). The Three R´s. *DESIGN STUDIES*, *1*(1), 4.

Bähr, B. (2012). Blended Prototyping. In J. Adenauer & J. Petruschat (Eds.), *Prototype! Physical, virtual, hybrid, smart ; tackling new challenges in design and engineering*. Form + Zweck-Verlag, Berlin.

Barati, B., Karana, E., & Hekkert, P. (2019). Prototyping Materials Experience: *International Journal of Design*, *13*(2).

Bardzell, J., & Bardzell, S. (2013). What is “critical” about critical design? *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI ’13*, 3297. https://doi.org/10.1145/2470654.2466451

Beaudouin-Lafon, M., & Mackay, W. (2007). Prototyping Tools and Techniques. In *The Human-Computer Interaction Handbook* (pp. 1043–1066). CRC Press. https://doi.org/10.1201/9781410615862-66

Bernhardt, A.-J. (2016). Wie man dem toten Hasen die Häuser erklärt. In *Manifestationen im Entwurf* (pp. 317–342). Transcript Verlag, Bielefeld. https://doi.org/10.1515/9783839431603-014

Blomkvist, J., & Holmlid, S. (2011). *Existing Prototyping Perspectives: Considerations for Service Design*. https://doi.org/10.21606/nordes.2011.012

Bredekamp, H. (2008). *Sankt Peter in Rom und das Prinzip der produktiven Zerstörung: Bau und Abbau von Bramante bis Bernini* (überarbeitete Ausgabe). Wagenbach, K.

Buchenau, M., & Suri, J. F. (2000). Experience prototyping. *Proceedings of the Conference on Designing Interactive Systems Processes, Practices, Methods, and Techniques - DIS ’00*, 424–433. https://doi.org/10.1145/347642.347802

Camere, S., & Bordegoni, M. (2016). *A lens on future products: An expanded notion of prototyping practice*. INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016.

Cannaerts, C. (2009). *Models of / Models for Architecture Physical and Digital Modelling in Early Design Stages*. https://doi.org/10.52842/conf.ecaade.2009.781

Colonnese, F. (2016). Die Erfahrung mit lebensgroßen Modellen im Entwurfsprozess. In *Manifestationen im Entwurf* (pp. 287–316). Transcript Verlag, Bielefeld. https://doi.org/10.1515/9783839431603-013

Coughlan, P., Suri, J., & Canales, K. (2007). *Prototypes as (Design) Tools for Behavioral and Organizational Change*. *43*.

Cross, N. (2001). Designerly Ways of Knowing: Design Discipline Versus Design Science. *Design Issues*, *17*(3), 49–55. https://doi.org/10.1162/074793601750357196

Dewey, J. (1929). *The Quest for Certainty: A Study of the Relation of Knowledge and Action*. New York: Putnam.

Dickel, S. (2017). *Irritierende Objekte: Wie Zukunft prototypisch erschlossen wird*. https://doi.org/10.6094/BEHEMOTH.2017.10.1.950

Dickel, S. (2019). *Prototyping Society—Zur vorauseilenden Technologisierung der Zukunft* (1st ed.). transcript Verlag, Bielefeld.

Diefenbach, S., Chien, W.-C., Lenz, E., & Hassenzahl, M. (2013). Prototypen auf dem Prüfstand. Bedeutsamkeit der Repräsentationsform im Rahmen der Konzeptevaluation. *I-Com. Zeitschrift Für Interaktive Und Kooperative Medien*, *12*, 53–63. https://doi.org/10.1524/icom.2013.0008

Dunne, A., & Raby, F. (2013). *Speculative Everything: Design, Fiction, and Social Dreaming*. The Mit Press.

Eco, U. (1989). *The Open Work by Umberto Eco (1989) Paperback*.

Ewenstein, B., & Whyte, J. (2010). Wissenspraktiken im Design. Die Rolle visueller Repräsentationen als"epistemische Objekte". In C. Mareis, G. Joost, & K. Kimpel (Eds.), *Entwerfen—Wissen—Produzieren: Designforschung im Anwendungskontext* (pp. 47–80). Transcript Verlag, Bielefeld.

Exner, K., Lindow, K., Stark, R., Ängeslevä, J., Bähr, B., & Nagy, E. (2015). *A transdisciplinary perspective on prototyping*. https://publica.fraunhofer.de/handle/publica/394477

Flechtner, R., Lorenz, K., & Joost, G. (2020). Designing a Wearable Soft-Robotic Orthosis: A Body-Centered Approach. *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 863–875. https://doi.org/10.1145/3374920.3375012

Frye, A. (2017). *Design und Improvisation: Produkte, Prozesse und Methoden*. Transcript Verlag, Bielefeld.

Gaver, W., Beaver, J., & Benford, S. (2003). *Ambiguity as a Resource for Design*.

Gengnagel, C., Nagy, E., & Stark, R. (2015). *Rethink! Prototyping: Transdisciplinary Concepts of Prototyping*.

Henderson, G. (2016). Why Make Models?, *The Architects' Journal* (blog). https://www.architectsjournal.co.uk/news/opinion/why-make-models.

Hertz, H. (1894). *Die Prinzipien der Mechanik in neuem Zusammenhange dargestellt...: Mit einem Vorworte*. Barth. http://archive.org/details/dieprinzipiende00hertgoog

Houde, S., & Hill, C. (1997). *What do Prototypes Prototype?*

Janda, V. (2018). *Die Praxis des Designs: Zur Soziologie arrangierter Ungewissheiten* (1st ed.). Transcript Verlag, Bielefeld.

Kannabiran, G., & Bødker, S. (2020). Prototypes as Objects of Desire. *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, 1619–1631. https://doi.org/10.1145/3357236.3395487

Khan, A. H., & Matthews, B. (2019). Democratizing Soap: The Methodological Value of Using Constructive Assemblies as a Participatory Design Tool. *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, 155–164. https://doi.org/10.1145/3294109.3295641

Kimpel, K. (2016). Design Prototyping for Research Planning and Technological Development. In C. Gengnagel, E. Nagy, & R. Stark (Eds.), *Rethink! Prototyping: Transdisciplinary Concepts of Prototyping* (pp. 23–35). Springer International Publishing. https://doi.org/10.1007/978-3-319-24439-6_3

Kirby, D. (2010). The Future is Now: Diegetic Prototypes and the Role of Popular Films in Generating Real-world Technological Development. *Social Studies of Science*, *40*(1), 41–70. https://doi.org/10.1177/0306312709338325

Knorr Cetina, K. (1998). Sozialität mit Objekten. Soziale Beziehungen in post-traditionalen Wissensgesellschaften. *Technik und Sozialtheorie*, *42*. https://pub.uni-bielefeld.de/record/2394965

Knuuttila, T. (2011). Modelling and representing: An artefactual approach to model-based representation. *Studies in History and Philosophy of Science Part A*, *42*(2), 262–271. https://doi.org/10.1016/j.shpsa.2010.11.034

Kordon, F. & Luqi. (2002). An introduction to rapid system prototyping. *IEEE Transactions on Software Engineering*, *28*(9), 817–821. https://doi.org/10.1109/TSE.2002.1033222

Lepik, A. (1995). *Das Architekturmodell der frühen Renaissance. Erfindung eines Mediums*. Wernersche Verlagsgesellschaft, Worms.

Lévi-Strauss, C. (1973). *Das wilde Denken* (H. Naumann, Trans.; 20th edition). Suhrkamp Verlag, Berlin.

Lim, Y.-K., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction*, *15*(2), 1–27. https://doi.org/10.1145/1375761.1375762

Mahr, B. (2012). On the Epistemology of Models. In G. Abel & J. Conant (Eds.), *Rethinking epistemology* (pp. 301–352). De Gruyter.

Mareis, C. (2016). *Theorien des Designs zur Einführung* (2., korrigiert). Junius Hamburg.

McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., & Vera, A. (2006). Breaking the fidelity barrier: An examination of our current characterization of prototypes and an example of a mixed-fidelity success. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1233–1242. https://doi.org/10.1145/1124772.1124959

McGrath, L., Bresciani, S., & Eppler, M. J. (2016). We walk the line: Icons provisional appearances on virtual whiteboards trigger elaborative dialogue and creativity. *Computers in Human Behavior*, *63*, 717–726. https://doi.org/10.1016/j.chb.2016.05.086

McLuhan, M. (1964). The Medium is the Message (1964). In *Crime and Media* (pp. 20–31). https://doi.org/10.4324/9780367809195-4

Niedderer, K. (2009). Relating the Production of Artefacts and the Production of Knowledge in Research. In N. Nimkulrat & T. O'Riley (Eds.), *Reflections and connections: On the relationship between creative production and academic research* (pp. 59–67). University of Art and Design Helsinki.

Oder, H. (2020). Entwerferische Dinge. In *Entwerferische Dinge*. Birkhäuser, Basel.

Oulasvirta, A., Kurvinen, E., & Kankainen, T. (2003). Understanding contexts by being there: Case studies in bodystorming. *Personal and Ubiquitous Computing*, *7*(2), 125–134. https://doi.org/10.1007/s00779-003-0238-7

Pfeffer, F. (2014). *To Do: Die neue Rolle der Gestaltung in einer veränderten Welt: Strategien | Werkzeuge | Geschäftsmodelle*. Schmidt, H, Mainz.

Polanyi, M. (1985). *Implizites Wissen: Übersetzt von Horst Brühmann* (H. Brühmann, Trans.; 1.). Suhrkamp Verlag, Berlin.

Rheinberger, H.-J. (1997). *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube*. Stanford University Press.

Rittel, H. W. J. (1973). *Dilemmas in a general theory of planning*. 15.

Rudd, J., Stern, K., & Isensee, S. (1996). Low vs. High-fidelity prototyping debate. *Interactions*, *3*(1), 76–85. https://doi.org/10.1145/223500.223514

Ryle, G. (1945). Knowing How and Knowing That: The Presidential Address. *Proceedings of the Aristotelian Society*, *46*, 1–16.

Sanders, L., Stappers, P. J. (2014a). Probes, toolkits and prototypes: Three approaches to making in codesigning. *CoDesign*, *10*(1), 5–14. https://doi.org/10.1080/15710882.2014.888183

Sanders, L., Stappers, P. J. (2014b). From Designing to Co-designing to Collective Dreaming: Three Slices in Time. *Interactions*, *21*(6), 24–33. https://doi.org/10.1145/2670616

Schmeer, J. (2019). Xenodesignerly Ways of Knowing. *Journal of Design and Science*. https://jods.mitpress.mit.edu/pub/6qb7ohpt/release/3

Schön, D. A. (1984). *The reflective practitioner: How professionals think in action*. Routledge, Milton Park, Abingdon, Oxon.

Schrage, M. (1999). *Serious Play: How the World's Best Companies Simulate to Innovate* (First Printing). Harvard Business Review Press.

Stachowiak, H. (1973). *Allgemeine Modelltheorie*. Springer.

Star, S. L., & Griesemer, J. R. (1989). Institutional Ecology, "Translations" and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420.

Suchman, L. (2002). Located Accountabilities in Technology Production. *Scandinavian J. Inf. Systems*, *14*.

Tost, J., Schuster, P. L., & Heidmann, F. (2022). Prototyping inconvenience: A pedagogical experiment on designing for debate in design education. *Interaction Design and Architecture(s) : IxD&A*, *51*, (pp. 81–110). https://doi.org/10.55612/s-5002-051-004

Wartofsky, M. W. (1979). *Models: Representation and the Scientific Understanding* (R. S. Cohen, Ed.). Springer Netherlands. https://doi.org/10.1007/978-94-009-9357-0

Wendler, R. (2013). *Das Modell zwischen Kunst und Wissenschaft*. Wilhelm Fink Verlag, München.

Wendler, R. (2016). Modellbegriffe als Element der Modellierung. In T. H. Schmitz, R. Häußling, C. Mareis, & H. Groninger (Eds.), *Manifestationen im Entwurf: Design—Architektur—Ingenieurwesen* (1st ed., pp. 271–285). Transcript Verlag, Bielefeld.

Wong, Y. Y. (1992). Rough and ready prototypes: Lessons from graphic design. *Posters and Short Talks of the 1992 SIGCHI Conference on Human Factors in Computing Systems*, 83–84. https://doi.org/10.1145/1125021.1125094

Yaneva, A. (2005). Scaling Up and Down: Extraction Trials in Architectural Design. *Social Studies of Science*, *35*(6), 867–894. https://doi.org/10.1177/0306312705053053

Yaneva, A. (2013). *Made by the Office for Metropolitan Architecture: An Ethnography of Design* (1.). NAI010 PUBL.

Yang, M., & Epstein, D. (2005). A study of prototypes, design activity, and design outcome. *Design Studies - DESIGN STUD*, *26*, 649–669. https://doi.org/10.1016/j.destud.2005.04.005

Table of figures

Rolf Brändle

Rolf Brändle is a PhD candidate at Bauhaus University Weimar. He grew up in Switzerland and after studying industrial design in Magdeburg and Potsdam, he began teaching and researching at the Folkwang University of the Arts in Essen in 2018. Nowadays, he lives in Leipzig, while working in between Essen, Oberhausen, Berlin and Weimar. In general, his work revolves around prototyping, model-making, crafts and material knowledge with a strong focus on sustainable and circular design strategies. At the Folkwang University of the Arts he is part of the Craft Lab within the *Sustainability by Design* Research project. There, he is researching how knowledge from sustainability research can be transferred through design to society and the local economy. In his PhD he is researching how knowledge production through designerly model practice can contribute to transdisciplinary sustainability research projects. As a practice based PhD, Rolf Brändle combines theoretical discourses around models and prototypes with case studies on designers using their model practices within transdisciplinary projects in sustainability research. He is therefore a Designer in Lab resident at the Fraunhofer Institute UMSICHT in Oberhausen as well as part of the “Forschungskreis” at the Weissensee School of Art and Design Berlin.

Paula L. Schuster

Paula L. Schuster is a PhD candidate at Humboldt University Berlin and University of Applied Sciences Potsdam. After completing her studies in communication in social and economic contexts at the University of Arts Berlin, Paula studied industrial and interface design at the University of Applied Sciences Potsdam, as well as Design Thinking at the Hasso-Plattner-Institute in Potsdam. From 2018 to 2022 Paula taught and researched as a part of the Interaction Design Lab (IDL) in Potsdam. There, her research interest in prototyping was deepened in the PROTOTYP research project, where she investigated prototypes as a communication medium of speculative futures. She focused on participatory prototyping during her involvement in the DISA project, addressing digital inclusion in the context of social anxiety. She has also worked as a freelance consultant for design processes and co-design in the cultural sector. In her PhD, her ethnographic research focuses on the methodology of Research Through Design. Her research question is how knowledge is produced by prototyping. She explores through a new materialist lens which practices turn prototypes into epistemic objects and what roles research prototypes take on.

Cultivating and Eliciting Felt Experiences for Design Use: Physical Manifestations of Abstract Bodily Experiences

Arife Dila Demir*, Estonian Academy of Arts
Nesli Hazal Oktay*, Estonian Academy of Arts
Kristi Kuusk, Estonian Academy of Arts

Abstract

Designing for bodily engagements requires cultivating and eliciting felt experiences that are related to the embodied concepts in question. Cultivation provides a source of bodily information through enabling and exploring bodily experiences, whereas elicitation renders that information in a form that can be analysed and articulated for use in design. In this paper, we present two projects, *Squeaky/Pain* and *Intimacy with Far-Away Bodies*, that start the design process with movement-based practices to harvest felt experiences by applying soma design and embodied design approaches. We analyse the cultivation and elicitation tools that are applied in these projects. As a result of the analysis, we offer a toolset for possible ways to cultivate and elicit the first-and-second-person felt experiences for design use. This toolset is intended to invite designers to employ and reflect on the translation of abstract bodily concepts into design prototypes.

Embodied design; Soma design; Cultivation; Elicitation; Prototyping

Traditionally, prototypes serve as tools for bringing ideas to life to communicate, validate, and refine them. Conventional prototyping begins with ideation followed by user research that is oriented towards solving wicked problems with a positivist approach. Such an approach typically disregards the felt bodily experience and the first-person perspective of the designer who may wish to challenge the positivistic design process by inviting ambiguity. Schön (1984) argues that “uncertainty, uniqueness, and value conflict are troublesome for positivist epistemology of practice” (pg. 42). A positivist approach may be more efficient for tackling a problem that is on firm, clearly defined, ground; however, situations that occupy the confusing and swampy lowlands tend to play havoc with purely technical solutions (Schön, 1984). In other words, technical solutions and positivist epistemology fail to accommodate the subjectivity of felt bodily experiences and first-person perspectives.

Working with bodily phenomena requires “staying with the trouble” (Haraway, 2016); it involves designing with uncertainty, uniqueness and subjectivity. Ambiguity thus becomes a “resource for design”’ (Gaver et al., 2003). Various approaches have been proposed to enable the design of close-to-body artefacts that engage with felt bodily experiences and with first-person perspectives (Höök, 2018; Loke & Robertson, 2013). Such approaches suggest engaging with unhabitual bodily experiences to gain insight for designing for bodily interactions, such as move-to-design/design-to-move (Höök, 2018; Loke & Robertson, 2013; Wilde, 2011). These approaches do not focus solely on solving problems, but rather aim to extend our understanding of bodily experiences and to develop new ways of designing for bodily engagements with materials or objects. Thus, these approaches provide insight into bodily concepts in relation to the self, others, materials and technologies located immediately on and around the body.

In this paper, we present two projects that provide an embodied perspective on designing with and for difficult bodily concepts. Rather than solving defined problems through a positivistic approach, we aim to extend ours and our users' understanding of bodily experiences through our prototypes. Specifically, we explore the concepts of chronic pain and of intimacy in remote communication. Our design processes set out to explicate difficult and evasive abstract concepts through prototypes to discover ways of thinking and living with these bodily concepts. Such design processes require a first-person understanding that is developed through the in-depth cultivation and elicitation of the bodily experiences in question. 'Cultivation' provides a source of bodily information through enabling and exploring bodily experiences, whereas 'elicitation' renders that information in a form that can be analysed and articulated for use in design. By reviewing the two design projects we aim to offer a toolset for the further cultivation and elicitation of felt experiences for design use.

The body as the locus of the design process

The projects that are presented in this paper are situated in embodied design (Wilde et al., 2017) and soma design (Höök, 2018), wherein the body is seen as the locus for the process of designing for close-to-body interactions. These approaches aim to improve our skills of sensory appreciation and knowledge of our bodies by accessing our lived experiences through bodily movements. Defamiliarization, in other words, engaging with unhabitual bodily movements can enable the acquisition of felt experiences (Bell et al., 2005; Crawford, 1984; Höök, 2018; Loke & Robertson, 2013) that triggers imagination in the design process (Wilde, 2011). To initiate defamiliarization, Höök (2018) suggests applying somatic practices i.e., yoga, dance or tai chi and offers 'somatic connoisseurship' that is consulting a somatic expert where the designer is not skilled in any somatic practice. On the other hand, designers may include materials into these unhabitual bodily engagements such as body sketching with the materials (Márquez Segura et al., 2016) that will sensitise to the bodily phenomena (Wilde et al., 2017) as well as to lived qualities of the materials.

These cultivated experiences are often tacit sensations that need to be made graspable through elicitation to be transferred into the design use. Elicitation provides access to felt experiences that may remain hidden otherwise. In other words, elicitation explicates the cultivated lived experiences through visual and textual tools. It has been suggested that visual and textual tools for eliciting felt experiences are combined to unpack the diverse aspects of the felt phenomena (Demir et al., 2022b). In this paper, we employ body maps of the human form to give visual expression to somatic experiences (Cochrane et al., 2022; Gastaldo et al., 2018; Ståhl et al., 2022). For textual elicitation, we employ semi-structured interviews (Frances et al., 2009), a lived-experience diary (Bolger et al., 2003) and a research diary (Given, 2008). These elicitation and cultivation tools are exemplified by the two presented projects, which thus provide the basis for our discussion of those tools.

Related works

Through employing embodied and/or soma design, various researchers have been cultivated first-and-second person lived experiences while bringing bodily concepts into the sphere of the physical being in the form of prototypes. For example, a designer's autobiographical exploration of neglected body parts informs the design of *Breathing Wings* (Tsaknaki, 2021); a group of designers' first-person exploration of menstruation manifests in shape-changing artefacts (Søndergaard et al., 2020); and a designer's examination of her breastfeeding experiences manifests in various wearable artifacts (Helms, 2021). Similarly, a first-person exploration of the pelvic floor area is materialized in *Pelvic Chair* (Ståhl et al., 2022) and a researcher's inquiry into her own research process inspired the work *Armour of Researcher* (Beuthel, 2022). These projects exemplify how first-person bodily explorations can inspire the design of prototypes. In general, soma and embodied design processes begin with designers' first-person investigations, which may then be combined with second-person explorations. For instance, informed first- and second-person accounts regarding the negative aspects associated with two people living far apart are materialized as wearable textile artefacts (Beuthel et. al., 2021). In *WORM-E*, its designers' personal somatic understanding, which inspired the form of their design, is then enhanced and broadened by the inclusion of design students, children, adults and a dancer, which in turn further develops and enhances their design process (Yavuz et. al., 2021).

To be informed by first-and/or-second person perspectives, these projects apply various methods for cultivating and eliciting felt experiences. Often, they start the design process with kinesthetic explorations for cultivating felt experiences. For example, the projects *Pelvic Chair* (Ståhl et al., 2022) and *Soma Mat* (Höök et al., 2015) use Feldenkrais exercises (a form of exercise therapy). On the other hand, for elicitation, many of these projects also employ body maps and interviews with participants (Anne Cochrane et al., 2022; Núñez-Pacheco, 2021; Beuthel et al., 2021) that serve the purpose of reflection, documentation, and to inspire further ideas. The two projects presented in this paper take inspiration from these previous works, by applying a similar approach to the design of bodily interactions in the context of bodily experiences of intimacy and pain.

From abstract bodily experiences into physical manifestations

In this section, we illustrate two design inquiries Squeaky/Pain and Intimacy with Far-Away Bodies that design with/for/through the bodies, translating abstract bodily sensations into concrete prototypes. The first project is situated in the context of chronic pain whereas the second focuses on intimacy in remote settings. The projects aim to extend our understanding of these concepts and alter the ways in which we experience chronic pain and intimacy in remote settings. Through each project, we discuss the cultivation and elicitation tools that we employed to inform the toolset for harvesting bodily felt experiences for design use.

Squeaky/Pain: The physical manifestation of chronic pain

Chronic pain is an invisible phenomenon that is woven into the fabric of everyday life, disrupting its daily flow and altering body perception. In experiencing chronic pain and to prevent possible pain triggers, people tend to develop a fear of movement (Singh et al., 2014) that prevents them from enjoying the things that they can do without triggering the pain alienating people from their bodies. Based on soma design (Höök, 2018), *Squeaky/Pain* considers engagement with pain in terms of an unhabitual bodily experience, suggesting that people may be able to develop somaesthetic awareness through a defamiliarized experience of their pain.

Squeaky/Pain (Demir et al., 2022a) facilitates mutual conversation between the pain and the body through movement-based interactions, to support somaesthetic awareness encouraging people to move and communicate with their pains. Squeaky/Pain*'* is the name given to the interactive wearable artefact that is a somatic extension designed to mimic the experience of pain and ranging from agony to relief. The project considers pain as a design material and designs with/in/through the bodies in pain. The project is informed by the felt experience of the designer, and participants who have upper-body musculoskeletal chronic pain. It employs first- and second-person perspectives in tandem to cultivate the pain experience for design use. The project unfolds in three phases: 1) the designer's bodily investigation; 2) participant study; and 3) the designer's engagement with the final prototype. Two iterations of Squeaky/Pain (Figure 1) were designed during the first and second phases of the project, while the third phase included testing of the final iteration. In this paper, the first two phases of the project are explained in order to illustrate how abstract bodily experiences can be converted into prototypes (Table 1).

Figure 1: The left image is the result of the first iteration of Squeaky/Pain and the right image is the result of the second iteration. Photograph by Mehmet Can Boysan.

Table 1 shows the design process of Squeaky/Pain, setting out how each step informs the creation of the prototypes. The text below the table explains how each method applied.

Squeaky/Pain						
Phase 1: *exploring with bodily movements* -Designer's bodily exploration of pain through yoga	**Phase 1: *textual elicitation*** -Designer's documentation of the sensations emerged during the yoga practice into her lived experience diary	**Phase 1: *visual elicitation*** - Designer's diary writings converted into a somatic experience map	**Phase 1: *material elicitation*** -Designer's life-size body map drawing onto a fabric -Exploration of different textile material and techniques resulted in the first prototype	**Phase 2: *exploring with movement through materials*** -Testing the first prototype with participants	**Phase 2: *textual & visual elicitation*** -Semi-structured interviews and body map drawings conducted with participants	**Phase 2: *material elicitation*** -Design of the second prototype informed by participants' reflections

The first phase started with a three-week long first-person exploration of pain where the designer –who is also a certified yoga instructor– practiced a yoga sequence that she had designed specifically to help relieve her own pain. Every day, after each practice, she recorded the experience in a diary that was later translated into a somatic experience map (Figure 2) and informed the interaction and design qualities of the prototype soma extension. For example, the designer wrote about the squeaky wood sounds that were coming from her body as she moved and this is illustrated as the sound of the pain in the somatic experience map. This aspect of her experiences also inspired the interaction modality of the prototype as she decided to use sound to trigger movement interaction. Following this she began material experimentation in order to construct a soma extension that represents the location of the pain experience visually. As a result, the first prototype mediates sound-motion interaction for the wearer. It creates a squeaky wood sound that mimics the agony of pain. When worn there is no way to turn the sound off completely; however, by moving very slowly the wearer can reduce the volume of the sound.

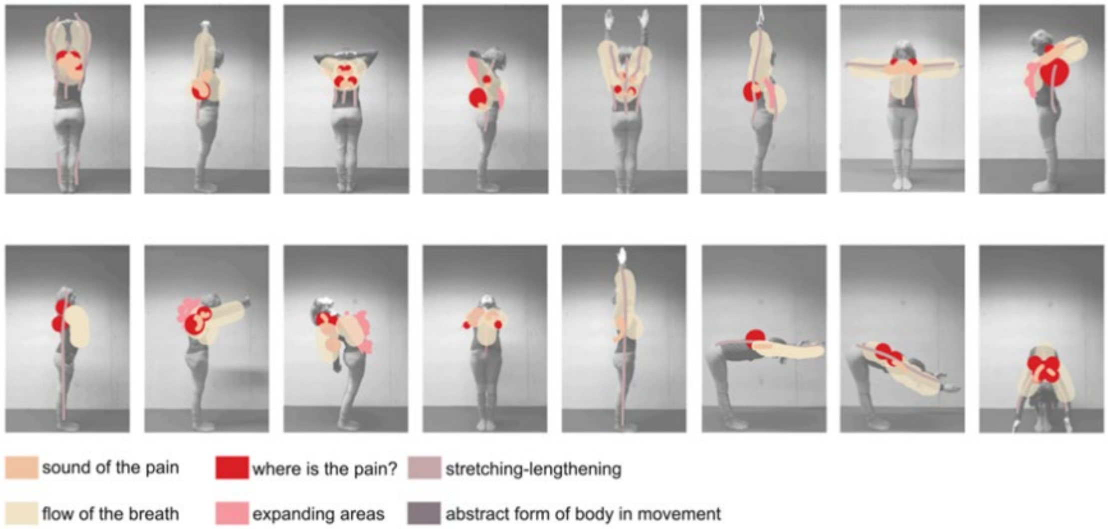


Figure 2: The somatic experience map illustrates the repeated aspects of the designer's yoga practice in relation to her pain that are recorded in her diary. Illustration by Arife Dila Demir.

The second phase was the testing of the prototype with three people, the design could thus be further informed by their experiences of pain in relation to the soma extension. The testing took place in one-on-one sessions that lasted one and a half hours each. Each session had four stages: 1) first interview; 2) guided breathing and moving exercise; 3) moving with soma extension; and 4) second interview. Both interviews were conducted as semi-structured interviews that were prompted with the body map drawings and were voice recorded for later analysis. The first interview provided insight into the participants' pain experiences in general whereas the second interview revealed their experiences with Squeaky/Pain, the soma extension. During the first interview, they visualised their pain experience in general on the body maps and in the second they illustrated their experience with the soma extension. These drawings were performed at the beginning of the interviews and participants began the conversation by explaining their drawings. To focus the participants' attention on their bodies in order to experience the prototype fully, the designer guided them to move and breathe during the second stage. In the third stage, while wearing the soma extension, the participants were invited to move as they wished. During the final interview, two participants revealed how relief from pain is itself part of the painful experience. This insight was brought to the second iteration, which was designed to represent the range of pain from agony to relief. To do so, it begins with the sound-motion interaction just as with the first iteration, and after that a pleasant sound feedback begins. Again, the wearer is required to move slowly, but this time to try to keep the volume level up.

This project showed that first-person exploration may result in design artifacts that may resonate with other people's bodily experiences. Similarly, second-person perspectives provided an insight into the somaesthetic affordances of the soma extension and brought forth new insight into the understanding of pain, showing that relief is itself also a part of the pain experience. Hence, it informed the designing of the second iteration of the artifact. Finally, while 'Squeaky/Pain' showed promise in providing interactions to facilitate somaesthetic awareness and relief, the qualities of bodily engagement provided by the soma extensions should be further explored in order to improve somaesthetic interactions.

Intimacy with far-away bodies: Physical manifestation of intimacy in remote connections

In the context of human relationships, the body plays an essential role in building and maintaining intimacy. However, in remote settings, intimacy is experienced without the physical closeness of the bodies. In *Intimacy with Far-Away Bodies*, the designer aims to create a bodily awareness of the far-away body in remote intimacies while designing for close-to-body engagements in remote settings.

Intimacy with Far-Away Bodies is an ongoing project, working with the sensory body as a creative material to design for people who are close by heart but physically apart. In this section, we show how somatic knowledge guided the designer during an embodied design ideation (EDI) process in developing new understanding and supporting the creation of a set of prototypes. The ideation session was built on a cultural probe study (Gaver et al., 1999) that collected personal insights about remote communication experiences from five participants. The participants were people who experience being physically apart from their loved ones for a period of time (Oktay, 2022). During this study, the participants were asked to observe and document their own experiences of remote communication with their loved ones. The study lasted for a week, resulting in eight keywords and three objects (Figure 3) that served as the input for ideation for Intimacy with Far-Away Bodies. The keywords were: loved, alone, relieved, not free, playful, energetic, caring, curious.

Table 2 shows the design process of Intimacy with Far-Away Bodies, illustrating how each step informs the creation of the prototypes.

<table>
<tr><td colspan="7">Intimacy with Far-Away Bodies</td></tr>
<tr><td>Cultural Probe Study</td><td>QiGong</td><td colspan="3">Somatic connoisseurship</td><td>Prototyping</td><td>Testing</td></tr>
<tr>
<td rowspan="2">Pre-step: gathering input for bodily movements

-Dancer gathering keywords from participants to inform Phase 1</td>
<td rowspan="2">Pre-step: exploring with bodily movements

-Dancer introducing QiGong practice to the designer</td>
<td>Phase 1: exploring with bodily movements through materials

-Dancer conducting embodied sketching with objects and keywords</td>
<td rowspan="2">Phase 2: Visual elicitation

-Designer’s visual analysis of the visual documentation</td>
<td rowspan="2">Phase 3: Textual and Visual elicitation

-Dancer’s semi-structured interview that was voice recorded by the designer

-Dancer’s body maps on the photos of the moving body from Phase 1</td>
<td rowspan="2">After-step: material elicitation

-Designer’s design mood boards

-Designer experimenting with materials</td>
<td>After-step: exploring with bodily movements through materials

-Designer testing the prototype with a participant</td>
</tr>
<tr>
<td>Phase 1:

Textual and Visual elicitation

-Designer’s observation notes on research diary

-Designer’s photo and video documentation</td>
<td>After-step: Textual and Visual elicitation

-Designer’s observation notes on research diary

-Designer’s photo documentation

-Participant’s semi-structured interview that was voice recorded by the designer.</td>
</tr>
</table>

In this project, the designer lacked expertise in somatic practices, therefore, she adopted the somatic connoisseurship method by collaborating with a dance artist who employs Qigong for improvisational dance. The somatic connoisseurship unfolded in three phases: 1) embodied explorations with a dancer; 2) analysis of phase one by the designer; and 3) a semi-structured interview and body mapping with the dancer (Table 2). Phase 1 began with a pre-step of movement-based explorations initiated with Qigong, a gentle movement practice that cultivates subtle energy by working with the moving body (Hung, n.d.). To familiarise the designer with the movement practices, the somatic expert led a QiGong session where the designer gained a first-person somatic experience, bringing the designer into closer contact with her body. Following that, the dancer performed body sketching using the objects and keywords that were generated during the cultural probe study (Figure 2). In Phase 2, the designer analysed the video recordings, photographs, and notes taken during Phase 1. In doing so, she prepared topics to discuss during the semi-structured interview and generated photos for body map drawing that is used as a visual complementary tool with the interview. In Phase 3, the designer conducted a semi-structured interview with the dancer and incorporated a drawing exercise making the dancer's experiences graspable for the designer.

Figure 3: The somatic connoisseur, in this case the dancer, explores with bodily movements through engagement with three objects provided by the designer. Photographs by Nesli Hazal Oktay.

This process of somatic connoisseurship resulted in a mood board (Figure 3a) then a set of prototypes. The prototypes had different forms, but the they all had the same function: they limited the bodily movements of the wearer in an attempt to disrupt habitual perceptions and ways of thinking (Loke & Robertson, 2013) in video calls: 1) A pillow placed on a chair during a video call mimics the ability to turn off the call when the person sitting on the prototype moves (Figure 4b); 2) a macramé piece that is placed on the wearer's back in alignment with their spine mimics the ability to turn off the video call when its wearer moves (Figure 4c); 3) a ball-shaped piece that is placed on the upper and lower body mimics the ability to turn off the video call when the person drops the prototype on the floor (Figure 4d). In sum, the prototypes were unhabitual objects, inviting their users to be more engaged with their bodies during video calls so that they have new opportunities to shape experiences with their loved ones when communicating that way.

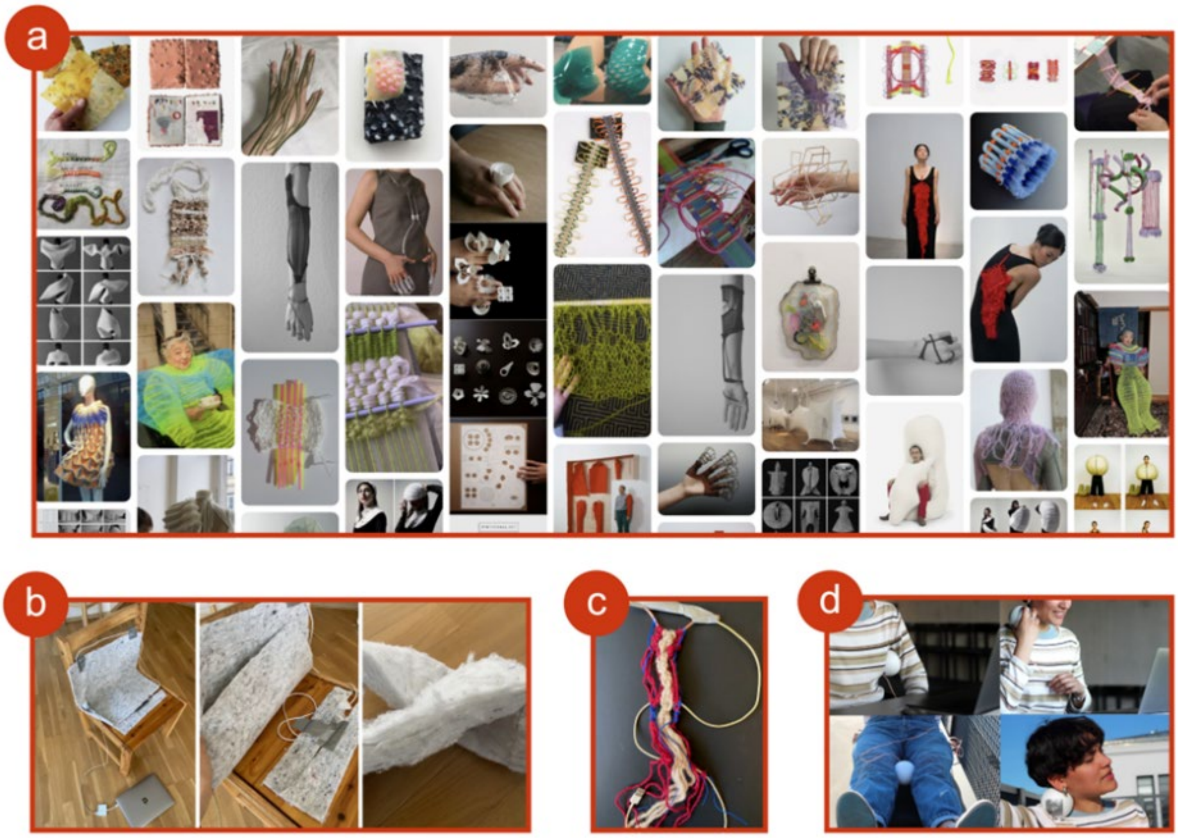


Figure 4: The mood board and the three prototypes created during Intimacy with Far-away Bodies. Illustration by Nesli Hazal Oktay.

The designer and her close circle interacted with the prototypes and provided feedback. After these experiences with the prototypes, the designer realised that prototype 3 (Figure 4d) had the most potential for creating bodily awareness because of its' closeness to the body and for its' potential for sensors to fitted if making it interactive. Next, an open call was made so that prototype 3 could be tested. A participant who experiences intimacy in remote connections, tested the prototype while having a video call with their mother who lives far-away. The call lasted for about 40 minutes and was conducted in a language that the designer does not understand in order to create a more comfortable environment for the participant. The designer observed the participant's interaction with the object, and recorded notes in her research diary and took photos. After 40 minutes, the designer interviewed the participant and audio-recorded the interview. The testing of prototype 3 provided insights into the emotional qualities and the material quality of this object.

The design process of *Intimacy with Far-away Bodies* unfolded with the designer's new understanding of how to design for people who are close by heart but physically apart. Additionally, it revealed how a second-person perspective may inform the creation of mood boards and ideas for design use. Cultivation and elicitation of the second-person felt experiences supported the designer in her attempt to transform the abstract embodied experiences of others into tangible sets of prototypes. The next step is to implement the test results and to iterate on the prototype.

Toolset for cultivating and eliciting felt experiences

The two presented projects exemplify how bodily experiences can turn into design prototypes informed by the felt experiences of pain and intimacy. They apply various cultivation and elicitation tools to inform the design process. Cultivation of bodily experiences provides rich data to be reflected upon whereas the elicitation methods explicate these subjective experiences, and make them more easily grasped by the designer. In analysing these two projects, we propose a toolset (Table 3) for cultivating and eliciting felt experiences for design use.

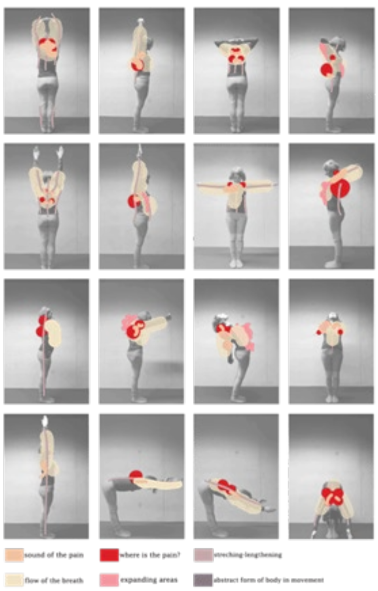
Table 3 presents the toolset for cultivating and eliciting the first- and second-person felt experiences for design use.

Cultivating Felt Experiences		***Eliciting Felt Experiences***			
Exploring with Bodily Movements	***Exploring with Bodily Movements through Materials***	***Visual elicitation**** ***(see Table 4 for the illustrations of below listed elicitations)***	***Textual elicitation***		***Material elicitation***
-Bodily explorations through somatic practices i.e., Yoga or QiGong	-Bodily explorations through materials i.e., prototypes or design props	-Body map (BM) drawings: 1) BM on the photos of the moving body; 2) standardised black outlined BM; and 3) life-size BM	-Semi-structured interviews	-Lived experience diary -Research diary	-Experimenting with materials/making/prototyping - Design mood boards

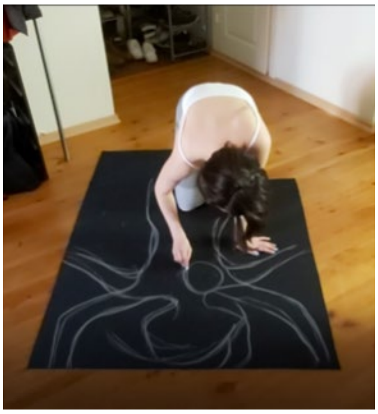
Designing for bodily experiences entails ‘cultivation of felt experiences’ at the beginning of the design process to gain deeper insight into the relevant bodily phenomena. This stage can begin with of first- and/or second-person engagements, however, we suggest that designers to first cultivate with first-person accounts. For this stage, we propose exploring bodily movements and with bodily movements through materials. The former tool can include engaging with somatic practices such as Yoga or QiGong. This will help designers and/or participants to experience their bodies in different shapes, forms and movements that are not habitual, thus, they can acquire new bodily realisations. The latter tool includes movement through the use of materials i.e., prototypes, design props or any material that is meaningful for the specific design project. In applying this method, designers can organise improvisational sessions where the movement with the materials has no strict rules, or they can integrate materials into somatic practices e.g. practising yoga while wearing the prototype. Both tools can be employed to cultivate combined first- and second-person experiences. If the designers are experts in any somatic practice, they can use their expertise to lead these sessions. Otherwise, they can consult a somatic expert in a method called ‘somatic connoisseurship’.

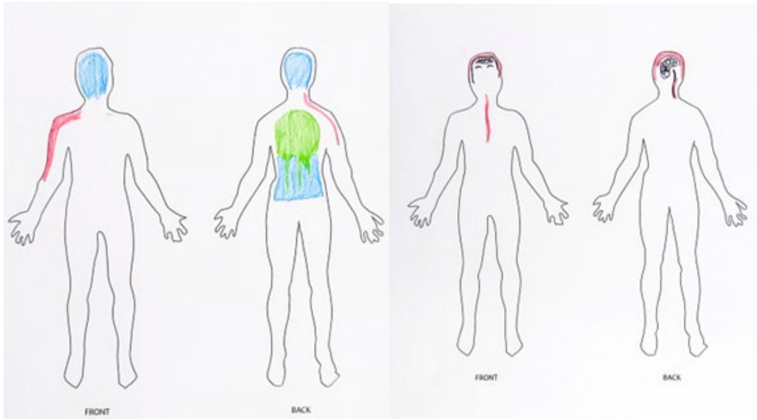
On the other hand, elicitation methods make lived experiences graspable and communicable for others. We offer three ways of elicitation that work as complementary tools 1) visual, 2) textual, and 3) material elicitation. For visual elicitation we offer body map (BM) drawings; BMs are tools to visually illustrate the felt experiences and they reveal aspects of such experiences that are otherwise difficult to communicate (Cochrane et al., 2022). BMs are generally applied as drawings on black-outlined human figures. In addition, we exemplify two other ways of approaching to BM method (Table 4). The first approach is to generate drawings on the photos of the moving bodies that are captured during the cultivation sessions. This kind of BM can be done by using drawing tablets. In this approach, people may better connect with the visual as it will involve photographs of their bodies and the photography may evoke their past experiences (Harper, 2002). Additionally, we propose exploring life-size BM drawings: this approach may capture the location of the felt sensations that are explored as well as the patterns that are generated and that can inform the visual design of the prototypes. Finally, we also see value in using standardised BM, especially, for example, when working with multiple participants and where the possibility of preparing photographic images for drawing is not possible or is not necessary for the investigation.

Table 4 shows three different ways of approaching the body map drawing: body maps on the photos of the moving bodies’ life-size body maps; standardised black-outlined body maps.

<table>
<tr><td colspan="2">Body Maps on the Photos of the Moving Bodies</td></tr>
<tr><td colspan="2">


</td></tr>
<tr><td>Life-Size Body Maps</td><td>Standardised Black-Outlined Body Maps</td></tr>
</table>





As textual elicitation tools, we propose lived experience diary and research diary. The lived experience diary can be used when the cultivation of felt experiences lasts for a longer period (e.g. a week or a month) so that the detailed nuances of the experiences in question can be logged. This tool can be applied both for first-and second-person elicitation. If the lived experience diary is used to document emerging sensations of particular embodied activities e.g. yoga or a dance session, we suggest writing the diary entries directly after these activities are undertaken and when the influence of the experience is still fresh in the memory. We suggest a research diary for taking observation notes when the cultivation sessions of second-person explorations happen in the presence of the researcher. Hence, they can document their interpretations of the other people's experiences to explicate them later in the elicitation sessions. We propose material elicitation as the final stage of the elicitation phase. At this stage, the explicated felt experiences come to a being through material investigation. This process may begin with design mood-boards (see Project 2) that are informed by the visual and textual elicitation to gather visual inspiration, or it can start directly with material engagement (see Project 1). For instance, engaging with various textile materials and techniques to ideate the forms and shapes of the prototypes. This dynamic process of material encounters will lead the design of prototypes that can be iterated as much as necessary according to what the projects entail.

In this section, we illustrated a toolset to articulate first-and-second-person felt experiences for design use. We offer this toolset for designers who wish to work with bodily topics and gain an in-depth understanding of the embodied phenomena that they want to study. This toolset is generated by the analysis of two presented design projects which shows that there is no one correct way of applying this toolset. Design processes are never linear; rather they circle back where some points of the process are entangled. As we have discussed, these tools can be applied in different orders as they make sense for the specific design inquiry with as many iterations as needed. In Figure 5, we illustrate how these tools are employed and shape the design process of two presented projects. Accordingly, we suggest that designers engage creatively and extend this toolset for designing for/with/through the sensory moving bodies.

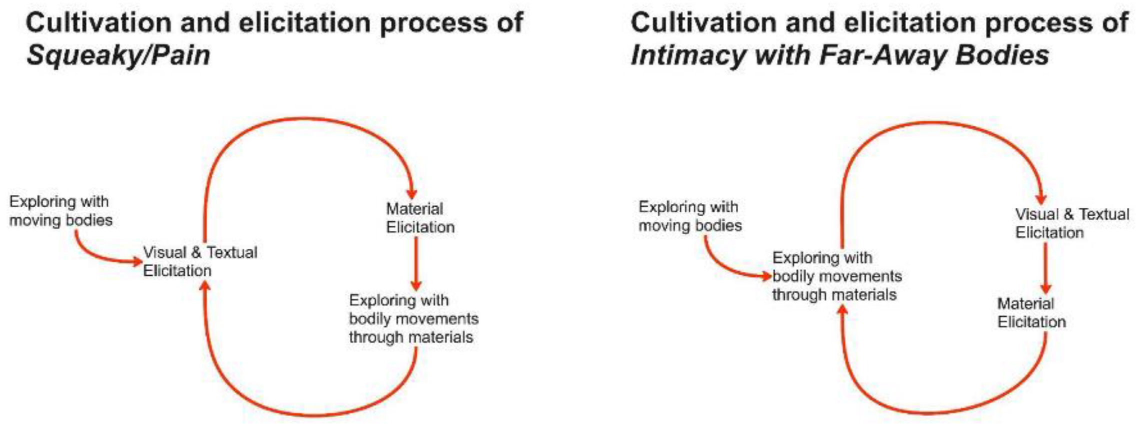


Figure 5: Cultivation and elicitation processes of Squeaky/Pain (left) and Intimacy with Far-Away Bodies (right), highlighting the non-linear nature of these processes. Illustration by authors.

Reflections on the toolset

We presented two design projects focused on chronic pain and intimacy in remote settings aiming to extend our perception and understanding of these embodied topics. Thus, they open up discussions on finding new ways of being and living in relation to these abstract bodily concepts. Through presenting these projects, we illustrated how felt experiences can inform the creation of prototypes. Additionally, we created a toolset for cultivating and eliciting the first- and second-person felt experiences for design use. This toolset provides a set of design methods that can be applied creatively according to the particularities of each embodied design inquiry. In this section, we will discuss the challenges that emerged in application of this toolset during the presented projects. These challenges bring out two notions to be considered when applying this toolset 1) being silly together; and 2) creating a safe space for all the parties involved.

To start the cultivation of felt experiences we suggest engaging with bodily practices. As we have illustrated in both projects this can happen through the designer's own engagement with somatic exercises, leading participants into such practices or by observing a somatic expert in their movement practice. Cases where designers lead a session while observing participants or observing the somatic expert may create uncomfortable situations for the ones being observed. To break this social awkwardness, we suggest being silly together with participants or the somatic experts involved in our design processes. By making unhabitual bodily movements together, all parties involved can feel equal in terms of social relations and this may help the ones being observed to better relax and focus on the activity of the cultivation session. The two projects we have described also illustrate how to practise being silly together: Firstly, in *Squeaky/Pain*, before the participants tested the artefact, the designer led them into a breathing and movement session where she also moved with the participants. They moved together and saw each other moving in strange positions, thus breaking the ice and helping participants to become more relaxed and comfortable wearing the artefact and moving by themselves. Similarly, in *Intimacy with Far-Away Bodies*, the designer first entered the world of movement through a QiGong session led by the somatic expert before the designer observed the expert while the expert conducted embodied sketching. In entering each other's world, they became familiar with each other and the way each other moved. In this way, the designers of both projects realised the value of being silly together with their participants and collaborators.

Our second point of discussion is the creation of a safe space for our participants, somatic experts and ourselves in the design-research process of bodily interactions. When we design with/for/through the body, we open what is private, intimate and personal to the public, thereby becoming vulnerable. In our attempts to gain insight into felt experiences we may find ourselves in a position where we risk invading personal privacy. On the other hand, purposeful vulnerability can also inform design works that focus on exploring unfamiliar experiences (Popova et al., 2022); it may trigger the formulation of on-the-spot responses for ethically grounded design processes. Working with bodies is working with the unknown and may require immediate alterations in the pre-structured design processes. We discuss that bodily design works should move beyond a consent-based ethical approach –without thereby abandoning consent procedures– and must create safe spaces for all parties involved in the study including ourselves and ready to take new actions as our design processes unfold. In terms of safe space, in *Intimacy with Far-Away Bodies*, the designer tested the prototype with a participant wherein the participant would engage with the prototype while having a video call with their loved one. The designer recruited a participant who would speak with their loved one in a language that was unknown to the designer. This way, she aimed for a safe space for the participant to speak out loud and have a conversation without the feeling of being listened to.

In summary, we propose being silly together and creating a safe space as necessary elements that should be considered in design works that aim to create bodily interactions and tackling sensitive personal topics. We have discussed how both of these elements can be employed in consideration of ethical and caring design processes, thereby providing comfort even while participants may experience potential discomfort in being vulnerable when sharing what is intimate, i.e., bodily sensations, emotions, feelings etc. In this way, we believe our design works may lead to caring prototypes and bodily interactions.

Conclusion

In conclusion, we regard prototyping as an ongoing procedure that is embedded in the open-ended process of design through a series of embodied actions. When working with the embodied and soma design processes, prototyping becomes imprinted into the designers' own bodies whereby our bodily awareness shapes our making and vice versa. In this way, our prototypes become physical manifestations of abstract bodily experiences. To thoroughly inform such design studies through the bodily experiences we need to develop better embodied insights. To do this, we offer the presented toolset in this paper anticipating that it can guide design inquiries that focus on bodily engagements. Designers can use this toolset to study the specific bodily concept that they aim to explore in their research or apply it to gain a general understanding of felt sensations to inspire their designs. We have illustrated the application of this toolset for explorative design studies that aim to extend our understanding of the specific bodily phenomena and to influence our perception. Moreover, we foresee that this toolset could also be used for designing prototypes that will reach end users. For instance, a design work that requires the bodily engagements of the users can benefit from this toolset by learning the diverse ways that how bodies move and feel.

References

Anne Cochrane, K., Mah, K., Ståhl, A., Núñez-Pacheco, C., Balaam, M., Ahmadpour, N., & Loke, L. (2022). Body Maps: A Generative Tool for Soma-based Design. Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction, 1–14. https://doi.org/10.1145/3490149.3502262

Bell, G., Blythe, M., & Sengers, P. (2005). Making by making strange: Defamiliarization and the design of domestic technologies. ACM Transactions on Computer-Human Interaction, 12(2), 149–173. https://doi.org/10.1145/1067860.1067862

Beuthel, J. M. (2022). The Armor of a Researcher: A Critical, Material Engagement with Somatic Experiences. Diseña, 20, Article 20. https://doi.org/10.7764/disena.20.Article.3

Beuthel, J. M., Bentegeac, P., Fuchsberger, V., Maurer, B., & Tscheligi, M. (2021). Experiencing Distance: Wearable Engagements with Remote Relationships. Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction, 1–13. https://doi.org/10.1145/3430524.3446071

Bolger, N., Davis, A., & Rafaeli, E. (2003). Diary Methods: Capturing Life as it is Lived. Annual Review of Psychology, 54(1), 579–616. https://doi.org/10.1146/annurev.psych.54.101601.145030

Cochrane, K., Mah, K., Ståhl, A., Núñez-Pacheco, C., Balaam, M., Ahmadpour, N., & Loke, L. (2022). Body Maps: A Generative Tool for Soma-based Design (p. 14). https://doi.org/10.1145/3490149.3502262

Crawford, L. (1984). Viktor Shklovskij: Differance in Defamiliarization. Comparative Literature, 36(3), 209. https://doi.org/10.2307/1770260

Demir, A. D., Nimkulrat, N., & Kuusk, K. (2022a). 'Squeaky/Pain': Articulating the Felt Experience of Pain for Somaesthetic Interactions. Temes de Disseny.

Demir, A. D., Nimkulrat, N., & Kuusk, K. (2022b). 'Squeaky/Pain': Cultivating Disturbing Experiences and Perspective Transition for Somaesthetic Interactions. Diseña, 20.

Frances, R., Coughlan, M., & Cronin, P. (2009). Interviewing in qualitative research. International Journal of Therapy and Rehabilitation, 16, 309–314. https://doi.org/10.12968/ijtr.2009.16.6.42433

Gastaldo, D., Rivas-Quarneti, N., & Magalhaes, L. (2018). Body-Map Storytelling as a Health Research Methodology: Blurred Lines Creating Clear Pictures. Forum Qualitative Sozialforschung / Forum: Qualitative Social Research, 19(2), Article 2. https://doi.org/10.17169/fqs-19.2.2858

Gaver, W., Beaver, J., & Benford, S. (2003). Ambiguity as a Resource for Design.

Gaver, W., Dunne, A., & Pacenti, E. (1999). Design: Cultural Probes. Interactions, 6, 21–29. https://doi.org/10.1145/291224.291235

Given, L. M. (Ed.). (2008). The Sage encyclopedia of qualitative research methods. Sage

Publications.

Haraway, D. J. (2016). Staying with the Trouble: Making Kin in the Chthulucene. Duke University Press.

Harper, D. (2002). Talking about pictures: A case for photo elicitation. Visual Studies, 17(1), 13–26. https://doi.org/10.1080/14725860220137345

Helms, K. (2021). Entangled Reflections on Designing with Leaky Breastfeeding Bodies. Designing Interactive Systems Conference 2021, 1998–2012.

https://doi.org/10.1145/3461778.3462048

Höök, K. (2018). Designing with the Body: Somaesthetic Interaction Design. MIT Press.

Höök, K., Caramiaux, B., Erkut, C., Forlizzi, J., Hajinejad, N., Haller, M., Hummels, C., Isbister, K., Jonsson, M., Khut, G., Loke, L., Lottridge, D., Marti, P., Melcer, E., Müller, F., Petersen, M., Schiphorst, T., Segura, E., Ståhl, A., … Tobiasson, H. (2018). Embracing First-Person Perspectives in Soma-Based Design. Informatics, 5(1), 8. https://doi.org/10.3390/informatics5010008

Höök, K., Ståhl, A., Jonsson, M., Mercurio, J., Karlsson, A., & Johnson, E.-C. B. (2015). COVER STORYSomaesthetic design. Interactions, 22(4), 26–33. https://doi.org/10.1145/2770888

Hung, H.-H. (n.d.). The Living Room QiGong—OPEN CLASS. Fienta. Retrieved 8 November 2021, from https://fienta.com/et/living-room-qigong-28483

Loke, L., & Robertson, T. (2013). Moving and making strange: An embodied approach to movement-based interaction design. ACM Transactions on Computer-Human Interaction (TOCHI), 20. https://doi.org/10.1145/2442106.2442113

Márquez Segura, E., Turmo Vidal, L., Rostami, A., & Waern, A. (2016). Embodied Sketching. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, 6014–6027. https://doi.org/10.1145/2858036.2858486

Núñez-Pacheco, C. (2021). Tangible Body Maps of Felt-Sensing Experience. Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction, 1–3. https://doi.org/10.1145/3430524.3442700

Oktay, N.H. (2022) Design placebos for the impossibility of empathy in videotelephony, in Lockton, D., Lenzi, S., Hekkert, P., Oak, A., Sádaba, J., Lloyd, P. (eds.), DRS2022: Bilbao, 25 June - 3 July, Bilbao, Spain. https://doi.org/10.21606/drs.2022.598

Popova, K, Garrett, R., Núñez-Pacheco, C, Lampinen A. & Höök K. (2022). Vulnerability as an ethical stance in soma design processes. In CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3491102.3501994

Schön, D. A. (1984). The Reflective Practitioner: How Professionals Think in Action (1st Edition). Basic Books.

Schön, D. A. (2017). How Professionals Think in Action. Routledge. https://doi.org/10.4324/9781315237473

Singh, A., Klapper, A., Jia, J., Fidalgo, A., Tajadura-Jiménez, A., Kanakam, N., Bianchi-

Berthouze, N., & Williams, A. (2014). Motivating people with chronic pain to do physical activity: Opportunities for technology design. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 2803–2812. https://doi.org/10.1145/2556288.2557268

Søndergaard, M. L. J., Kilic Afsar, O., Ciolfi Felice, M., Campo Woytuk, N., & Balaam, M. (2020). Designing with Intimate Materials and Movements: Making 'Menarche Bits'. Proceedings of the 2020 ACM Designing Interactive Systems Conference, 587–600. https://doi.org/10.1145/3357236.3395592

Ståhl, A., Balaam, M., Ciolfi Felice, M., & Kaklopoulou, I. (2022). An Annotated Soma Design Process of the Pelvic Chair. Designing Interactive Systems Conference, 1921–1933. https://doi.org/10.1145/3532106.3533469

Tsaknaki, V. (2021). The Breathing Wings: An Autobiographical Soma Design Exploration of Touch Qualities through Shape-Change Materials. Designing Interactive Systems Conference 2021, 1266–1279. https://doi.org/10.1145/3461778.3462054

Wilde, D. (2011). Extending body and imagination: Moving to move. 10(1), 31–36. https://doi.org/10.1515/ijdhd.2011.004

Wilde, D., Vallgårda, A., & Tomico, O. (2017). Embodied Design Ideation Methods: Analysing the Power of Estrangement. 5158–5170. https://doi.org/10.1145/3025453.3025873

Yavuz, S. U., Kuusk, K., & Honauer, M. (2021, June 8). Designing Somatic Play for Digital Natives through a Bodycentric Design Process. Proceedings of Design Culture(s)- Cumulus Roma 2021.

Arife Dila Demir*

Arife Dila Demir is a junior researcher and PhD candidate at the Estonian Academy of Arts. Since 2019 she also teaches at the academy as a contractual lecturer. Her work is focused on explicating chronic pain through movement-based interactive wearable textiles for somaesthetic awareness. Dila is involved in somatic practices, i.e. yoga and dance improvisation, which she interweaves with her design research. Her research background is in soma design, somaesthetics, kinesthetic interactions, interactive textiles, Human-Computer-Interaction, autoethnography, and first-person research methods.

Nesli Hazal Oktay*

Nesli Hazal Oktay is a designer-researcher and educator focusing on the impacts and interactions the emerging technologies could deliver. She holds an MA in Interaction Design from the Estonian Academy of Arts in Tallinn and a Communications BA from the Galatasaray University in Istanbul. Since the academic year 2019/20, she is working as a visiting lecturer and also as a curriculum developer of the Interaction Design MA at the Estonian Academy of Arts. As an educator, she has led several industry collaborations, and her subjects are shaped around interaction design and speculative design. She is also a Ph.D. candidate at the Academy and her research interests include embodied, participatory, and speculative approaches to design.

Kristi Kuusk

Kristi Kuusk is a designer-researcher working on the direction of crafting sustainable smart textile services. She is looking for new ways for textiles and fashion to be more sustainable through the implementation of technology. In 2016 Kristi presented her PhD project on craft and sustainability qualities in smart textile services at the Eindhoven University of Technology in Designing Quality in Interaction research group. The related collaborative design work has been presented in various international exhibitions, shows and conferences. Her PhD work related to Augmented Reality on textiles was granted a patent in 2018 and commercialised by an industrial partner. Today Kuusk works as a senior researcher in textile futures at the Estonian Academy of Arts Design Faculty running Sensorial Design group. She has collaborated as a selected laureate in the EU projects 'STARTS Residencies' and 'WORTH Partnership Project'.

*Joint first authors/equal contribution.

Creating translational knowledge: the role of visual communication design and prototyping methods in the research process

Cathryn Anneka Hall, University of the Arts London
Laura Knight, University of the Arts London
Veronika Kapsali, University of the Arts London

Abstract

This paper explores the role visual prototyping by visual communication designers can play in the navigation and communication of textile design research. Typically, visual communication is only applied to dissemination of research activities – which happens at the end of a project. The authors argue that visual communication has more to offer when it is included as core element of the research process supported by visual prototyping. Using an illustrative case study of the Bio-Inspired Textile research project at University of the Arts London in collaboration with students from the Graduate Diploma Graphic Design course, the authors discuss how this was explored in practice and the benefits of such an approach. Here the project was conducted between textile design researchers and graphic design students who took on a student-as-researcher role. The Bio-Inspired Textiles research explores how eight different structures found in nature can be applied by textile designers. The communication designers were asked to explore these structures and communicate them through physical and digital typographical prototypes. Using an after-action review method, the paper discusses the insights of the project from both researchers and student perspectives. The authors conclude that visual communication designers can play a vital role within a research process and their methods, such as prototyping, enables the creation of new translational knowledge and its application into design practice.

Visual communication design; Prototyping; Student-as-researcher; Textile research; Knowledge exchange; Translational Knowledge

Traditionally, Graphic design has focussed on developing visual communications in response to client-needs (Wragg & Barnes 2016). In research, this role is often restricted to the dissemination of results. However, there is now a growing demand within industry and academia for a new type of designer. One with the '*expanded capacity*' to undertake and participate in research (Vaughan 2017). In our world full of challenges and 'wicked problems' (Rittel and Webber, 1973), the research space is expanding to encompass interdisciplinary teams that could benefit from the integration of visual communication into the research process as part of the creation of new knowledge.

This paper explores the potential of the role of visual communication designers as researchers, rather than solely as a disseminators of results. The paper describes a knowledge exchange collaboration between visual communication students at University of the Arts London (led by Author2) and Bio-Inspired Textile team (Author1 and Author3), working on an interdisciplinary research project. The Bio-Inspired Textile research aimed to translate knowledge from the field of material science (Naleway et al., 2015) regarding the ways biological structures create extraordinary properties compared to the simple materials that they are made of. Fundamentally, the research focused on how the structural lessons found in nature could be applied to textile design and practice.

Working with Bio-Inspired Textile researchers, the students on the Graduate Diploma Graphic Design course received a live brief providing them with the unusual student-as-researcher role rather than a more typical student-as-professional role. Through a six-week collaboration, the students created 15 typographical prototypes which were used to explore how the biological structures could be translated for a textile design audience. Reflection-in-action (Schön, 1983) followed by an after-action review (Morrison and Meliza, 1999) was used to establish what had happened and what role visual communication had played in the process of creating new knowledge.

The paper concludes that working with visual communication designers and their prototyping methods helped to bring a different perspective – as non-textile experts - and clarity over the key messages needed to translate the biological structures from the material science field for designers. In doing this, the visual communication designers played a vital role in the research process, allowing the Bio-Inspired Textile researchers to create new translational knowledge about the structures for their application into textile design. In exchange, the students gained an advanced level of experience, not only with information regarding the biological structures, but as active participants (students-as-researchers) in the research process through prototyping.

Visual Communication & Research

In academic research, visual communication is generally employed to disseminate outcomes and findings, which happens at the end of a project. Outcomes, outputs and dissemination are all common terms that describe visual communication activities in their relationship to research. This suggests that visual communication happens in service of the research. This is consistent with commercial practices in visual communication where the goal is to achieve communicative efficiency of given content (Frascara, 1988). The knowledge created in the process of developing the communication is rarely discussed, as such designers have faced epistemological and methodological challenges in establishing an evidence-base for visual communication (Wragg & Barnes, 2016). Where visual forms of knowledge production are seen to lack the 'unambiguous capacities' of numerical and textual representations (Drucker, 2014), it is contested whether these processes can generate knowledge (Renner, 2017). However, Hinrichs et al (2018) counter this by suggesting that visual communication can serve more than one purpose in research. Apart from its role in communicating already existing insights and knowledge, it can also *'facilitate exploration'* in order to arrive at *'new discoveries*'.

To understand how this might happen, practice-led approaches provide a theoretical frame to establish how images can generate meaning in research, particularly through prototyping (Renner, 2010). This paper argues that the exploratory processes of prototyping, reflection, and critique (Poggenhohl, 2018) that designers use to develop their understanding of a problem have something to offer when included as a core element of the research process.

Prototyping in Research

Prototyping is generally exploratory and iterative; a process used to generate knowledge to inform a larger system. O'Leary (1998) notes that prototyping is a particularly useful and flexible tool for investigating nonnumeric and symbolic information. Normans' theory of the 'cognitive artifact' (1991) offers a useful frame to understand how this process might work. He proposes that all design can be understood as an act of representation and therefore, is concerned with cognitive artifacts. Normans defines the cognitive artefact as an '*artificial device'* that '*serves a representational function'* affecting human cognition. In this view, a prototype can be thought of as both a form of cognitive support and as feedback in a research process (Boyd Davis & Vane 2019) as they capture and 'externalize' a design, and thinking in process.

There is a growing body of literature discussing the role of visual prototyping, specifically in interdisciplinary research. For example, in the field of Digital Humanities, designing and prototyping are considered '*core activities*' by Galey and Rueker (2010). In their paper, which explores prototypes as theories, the authors explore whether the arguments embodied by prototypes are 'contestable, defensible, and substantive', and further question whether the prototypes themselves might be considered original contributions to knowledge. Galey and Ruecker suggest three broad functions of a prototype.

- Prototype as tool: functions as an affordance that is used to carry out a given task
- Prototype as experiment: functions as a process that is used to test a theory
- Prototype as theory: functions as an externalisation that is used to communicate an interpretation

However, as Hinrichs et al (2021) note, each of Galey and Rueckers definitions present prototyping as a means-to-an-end. They argue that a prototype can in fact function as *'an object of inquiry with its own mediating characteristics'.* The idea of a design as mediation or translation is particularly relevant in interdisciplinary research, where researchers bring different knowledge, understandings and languages to a project (Ribul & de la Motte, 2018). Specifically in the field of Design, Poggenhohl (2018) suggests that prototypes can play a vital role in making visible to everyone involved what is '*known, half-baked and faulty*' about an emerging design problem. This paper builds on the idea that prototyping in design can be used as a form of translation but rather than focussing on exploring a design problem, we investigate this in the context of research.

Visual Communication & Education

Visual communication as a subject is 'more typically associated with vocational training than knowledge-production' (Nelson, 2013:3). The focus of the practice is often to address and solve an articulated problem. Consequently, studio-based pedagogies in design education are structured to emulate professional practice (Motley, 2017). These 'signature pedagogies' are defined by Shulman (2005:52) as the '*types of teaching that organise the fundamental ways in which future practitioners are educated for their new professions*.' For example, the 'live brief' is a signature pedagogy in design education. Here, an external client sets a creative brief for students and the student-designed responses generate creative visual 'solutions' for the client. This type of project-based learning positions the student-as-professional, requiring them to work as 'design experts;' employing implicit knowledge to 'conceive and develop original products, services, and communicative artefacts' (Manzini, 2015:65). The outcomes of such projects are discussed through critique, where the focus of the discussion is generally on their 'appropriateness' as a 'solution' to the given problem (Cross, 1999, Norman, 1991).

Yet, Drucker (2014) speculates that as visual communication programmes are required to respond to more sophisticated problems, they will require a corresponding sophistication of analysis and knowledge production. Therefore, there needs to be a shift in focus from solely problem solving, where students communicate knowledge that is embedded in their visual design solutions (student-as-professional) to an additional focus on the student-as-researcher. In this new researcher role, students communicate explicit knowledge through process and prototyping to create design knowledge (see Table 1). Therefore, to focus on knowledge production in visual communication, the case study outlined in this paper considers the student-as-researcher and their methods (prototyping) where the design process is viewed not just as one of problem solving but one that aims to 'produce knowledge useful to those who design' (Manzini, 2009:5).

Table 1. Defining the two different roles: student-as-professional and student-as-researcher

Role	**Focus**	**Communication**	**…in order to produce**
student-as-professional	address and solve an articulated problem	implicit knowledge embedded in outcomes	creative visual solutions
student-as-researcher	prototyping	explicit knowledge communicated through process	design knowledge

Bio-Inspired Textiles

Bio-Inspired Textiles (BIT) is an Arts and Humanities Research Council funded research project that combines the fields of biology, material science and design (specifically textile design but also visual communication design as this paper discusses). One of the aims of the research was to develop a practical framework to help textile designers access relevant lessons concealed within the field of material science regarding the extraordinary mechanical properties observed in biology that are the result of structural design.

For example, *nacre* otherwise known as *mother of pearl*, is found in the lining of the Abalone shell. Nacre is primarily composed of chalk, a substance known to be brittle, alongside a nominal amount of protein. It follows that one would expect nacre to be quite brittle, but it can be up to one thousand times more resistant to cracking than chalk alone because of the way the chalk and protein is structured (Barthelat *et al.*, 2007).

As with any scientific discipline, designers find the knowledge from material science, with their mathematical equations, microscopic imagery and discipline specific language, difficult to engage. The gap between the knowledge presented in material science field exploring relationship between the structure (layers) and function (strength and crack resistance) of the Abalone shell and textile practice is wide. This is evident in the limited examples of textile designers drawing on biological structural design from the literature. Such activities tend to be research centred and niche in design (Kapsali and Hall, 2022), but commonplace in material science. Bridging this gap constituted one of the main challenges for the BIT researchers.

Bio-Inspired Textiles and Communication

In order to translate the relevant lessons from biology for textiles designers, BIT researchers drew on the work of Naleway et al. (2015) whose review of the relationship between structure and function in biological materials that demonstrate advanced mechanical behaviours revealed eight recurring structures. The consolidation of such a vast body of knowledge into eight biological structural design elements provided a more consistent framework of terminology for the material science community. However, Naleway at al. took this one step further by providing graphical representations of each biological structural design element offering greater clarity to his audience (Figure 1) and in doing so, created a visual language, accessible to designers and set the scene for non-specialist audiences to engage with this information.

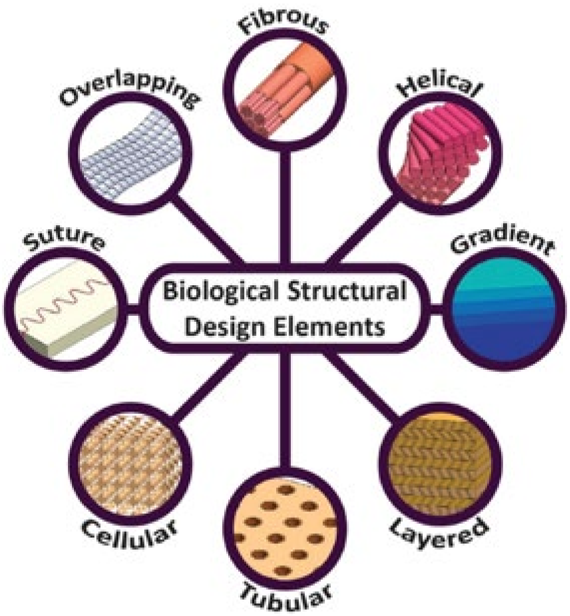


Figure 1. Naleway et al.'s (2015) graphical depiction of the eight most common biological structural design elements.

Typically, in the scientific disciplines, photographic images, such as those from under a microscope are presented to aid understanding. Comprehending the meaning of these photographic images involves experience and specialist training, skills designers do not typically possess. This makes it easy for the information encoded within the photographic image to be misunderstood by the designers. The translation by Naleway et al. (2015) of a photographic representation into a graphic representation (more commonplace in the design disciplines) provides a more accessible way for design researchers to access and apply the knowledge.

In addition to the graphic representations, Naleway et al. (2015) used a combination of photographs from under the microscope and literal photographs of the source of the example to fully communicate the structures. The three visual elements were the key to the translation for the designers (figure 2). Figure 2 demonstrates the layered structure, described in the text as "composite materials that consist of multiple layers or interfaces and are often employed to improve the toughness of otherwise brittle materials" (Naleway et al. 2015:5461). This is first, visually, explained using a graphic representation of the structure followed by a photograph of a biological specimen, in this case the Abalone shell (mother-of-pearl). Finally, physical details of the layered structure are presented with accurate microscopic imagery revealing the layers found in the lining.

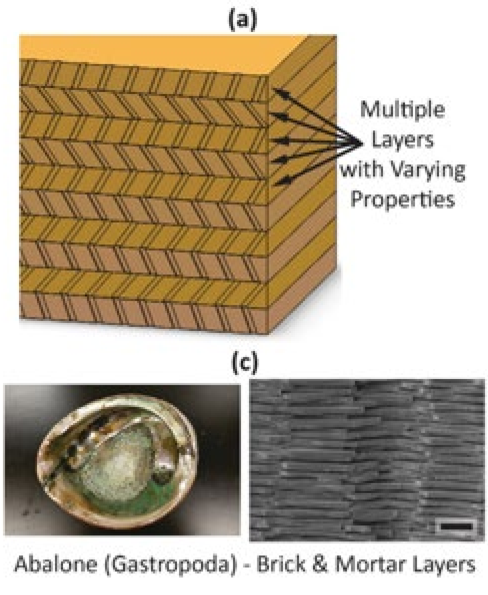


Figure 2. Naleway et al.'s (2015) three types of imagery used to explain biological structural design elements (Top: Naleway et al.(2015), Bottom: adapted by Naleway et al (2015) with permission from Barthelat at al. (2007), Copyright 2007, Elsevier)

The combination of all three of these images represent information that is not necessarily spelt out in the text, often accepted as tacit knowledge for those in the material science field. It was the combination of these visuals, especially the graphic, that enabled the translation of knowledge to be easier to understand by the designers. However, the leap from understanding this information and how it can be successfully applied into textile practice, such as a weave or knit structures was still to be established. It is the application of this knowledge for a textile designer that provided the challenge for researchers to investigate alongside visual communication designers.

Methods

This research was conducted between textile design researchers (Cathryn Anneka Hall and Veronika Kapsali) working on the BIT research project and thirty-two visual communication students undertaking their Graduate Diploma at University of the Arts London led by Laura Knight. The collaboration, which took place between February and March 2022 was designed to involve the graphics students, not as a dissemination exercise or playing the more traditional role of problem solver for a commercial client (student-as-professional) but they were asked to become part of the research process (student-as researcher).

The collaboration was set up as a knowledge exchange activity. Using a live brief, the students were asked to explore the structures in small groups using typographical prototyping as the main tool of investigation. Typographic design was chosen as the visual communication activity as it addresses two important but distinct creative challenges that are relevant to the research; syntax and semantics. Syntax relates to the 'essential or structural forms' of the type (Johnston 1962). Semantics addresses how typography evokes meaning through visual association (Carter, 2007). Typographic design balances both aspects. In total fifteen prototypes were produced by the students which were analysed by the Authors to establish the findings presented here.

Working in this way, the BIT researchers could obtain a non-textile perspective and highlight areas of confusion within the communication of their framework. The project was conducted across a six-week period where the BIT researchers actively engaged with the students on three occasions: to brief the students in the task, provide interim feedback and view the final presentations. One student project is used as a case study to exemplify the process that was taken during the collaboration and demonstrate how prototyping was used. However, all fifteen prototypes were analysed for the research and key examples from across the students' work are used for the discussion of the insights.

Reflection was made by the researchers throughout the collaboration, as a form of reflection-in-action (Schön, 1983), but was only formalised during after action review (Morrison and Meliza, 1999) in which questions such as 'what happened?', 'what went well?', or 'what could be changed?' were asked. Finally, the paper also draws on the reflections made by the students themselves to present both the researchers and students-as-researchers perspectives leading to the insights presented in this paper.

Visual Communication Design Collaboration

The visual communication design collaboration was the third collaboration during the research project. To first, address the challenge of translating Naleway et al.'s (2015) eight Biological Structural Design Elements for a textile design audience, the BIT researchers attempted to outline the relevant design lessons within each structure themselves. To test how this could be applied to textile design, the BIT team piloted two collaborations, one with professional textile designers and second with Graduate Diploma Textile Design students. By working with these two textile specific audiences, the researchers refined their understanding of the design lessons and began to establish how they could be applied to a variety of textile techniques (yarn spinning, knitting, weaving, embroidery, fabric manipulation etc…). Although the communication between the researchers and the textile designers in these two pilots had demonstrated, in the most part, an understanding of the structures and their application to textile practice, it had also highlighted key points of confusion. Thus, it became clear that further refinements were required to bridge the gaps between science and design practice.

The collaboration between the BIT researchers and the Graduate Diploma Graphic students was established to explore these required refinements. The collaboration was created as a knowledge exchange activity to position the students-as-researchers rather than the typical student-as-professional approach used in the dissemination of research outputs/ findings etc, The BIT researchers provided students with experience of an interdisciplinary research brief and the students provided a non-textile perspective of how the structures could be communicated for a specific textile audience. In this way many of the assumptions and tacit knowledge held by both the BIT researchers (both textile designers) and the textile professional and textile student collaborators could be stripped away and further clarity of the key textile design lessons found in biology was obtained.

Bio-Type Project

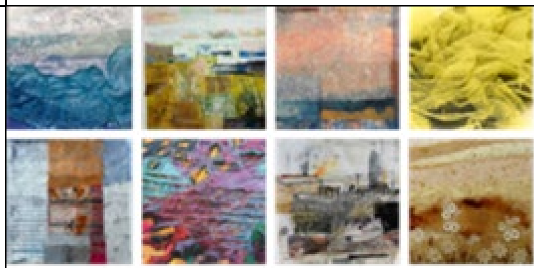
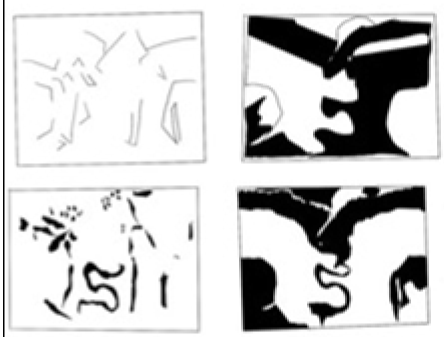
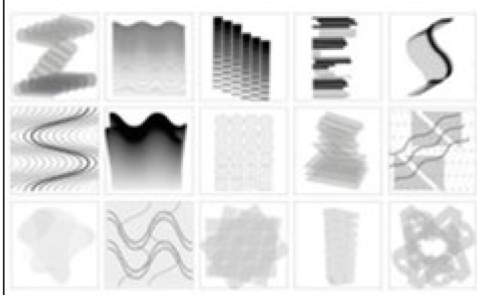
The project, called Bio-Type, asked a group of thirty-two graphic design students to work in groups of two to translate a single Bio-Inspired Design structure into typography as both an alphabet, and a piece of moving imagery, that spells out the name of the structure.

As discussed, this knowledge had already been visually translated into photography and in graphic forms by Naleway et al. (2015). While these enabled the translation of knowledge for the designers, the link to its application into textiles (such as weave or knit structures) was less clear. The main communication challenge was therefore that the essential structures needed to be communicated alongside their creative potential in application. Typographic design was used as the visual communication activity in two ways: syntax (essential structural forms) and semantics (meaning through visual association). To address syntax, alphabets are designed as a series of distinct visual signs, each with its own structural norms. Students would therefore need to explore the ways that the Bio-Inspired structures could be clearly communicated through the basic structures of the letterforms. In addition, the students addressed the communication semantically in their material and visual choices. This provided the opportunity to visually link the Bio-Inspired structure's to their creative application in textile practice.

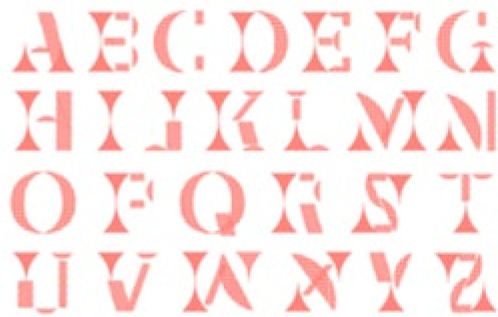
Students were required to use prototyping to develop their understanding of the concepts. They were asked to generate a wide range of prototypes using different materials, methods and processes and as the project progressed, narrow down and commit to one concept. Using further prototyping, they were then able to develop a set of letterforms that communicated their interpretation of the structure.

As table 2 describes, teaching and learning was delivered through workshops and studio critiques supported by readings and technical learning. The BIT researchers' interactions with the students were deliberately planned across the project at specific points to create knowledge exchange.

Table 2. BioType Project Structure across six weeks

Week	Activity	Output Examples
1	**Brief launched** Students allocated a group and structure and asked to complete the following visual research tasks. 1. Collect 30 images that communicate their structure 2. Produce 10 iconic prototypes based on a single image from the found images 3. Generate 50 symbolic prototypes based on their structure These visual prototypes enabled the students to develop a basic understanding of their structure and begin exploring the possibilities for communicating it visually.	 *Figure 3. Image research into the layered structure, Credit: Yujuan Cui*  *Figure 4. Iconic prototyping of the layered structure, Credit: Moeko Doi*  *Figure 5. 30 symbolic prototypes of the layered structure, Credit: Moeko Doi*

	Exploration Workshop Building on their visual research, students further explored their understanding of the structures through collective drawing and paper model making. These visual and physical prototypes further developed their understanding of their structures through processes of collaborative making and discussion.	 *Figure 6. Paper prototyping of the layer structure, Credit: Laura Knight*
2	**Briefing with BIT** Researchers presented: • the BIT research • the structures • design questions for each structure Following the briefing, students were asked to evaluate their prototypes so far, using the design questions set out in the briefing. They were asked to choose the three they considered to be the most effective or consider developing further prototypes based on the design questions.	
	Studio Students presented their chosen prototypes in a studio critique. Prototypes were discussed and evaluated in terms of: • their effectiveness in visually communicating the structure • their potential for development as a response to the design questions	 *Figure 7. Prototype presentation for Layer structure, Credit: Yujuan Cui and Moeko Doi*

3	**Typographic system prototyping workshop** Students begin to explore typographic systems - using rule-based drawing around a single structure to explore scales of visual dimensions.	 *Figure 8. Typographic system prototypes for Layer structure, Credit: Yujuan Cui and Moeko Doi*
4	**Presentation of prototypes to BIT**	 *Figure 9. Chosen prototype for BIT presentations, Credit: Yujuan Cui and Moeko Do (see also Fig.13)*
5	**Final studio** Peer critique of final proposals	
6	**Final presentations to BIT** *See Fig.13 & 14*	

Case Study: Layered Structure

At the end of the BIT research project (after the collaboration) each design lesson obtained from the structures found in biology was distilled into a simple text relevant to textile designers. The graphic design students' work formed part of the methods that provided this clarity. For layered structures this message is as follows: “Biology can teach us how layers combine materials in different ways for specific jobs” (Bio-Inspired Textiles, 2022).

Just like the Abalone shell with its brick-and-mortar layers of chalk and protein that ensures the mother-of-pearl is stronger and more crack resistant than if it had been made up of either chalk or protein alone, textile designers can ask themselves how they can combine and position textile materials to create specific functions. The example provided by the BIT researchers, is a quilt made from three layers of materials: a woven textile on top, a filler textile in the middle and a softer textile at the bottom. Alone, none of these textiles achieve what all three materials create together.

However, to reach this clear explanation of how layered structures can inform the way we design textiles, the graphic design students explored how this structure could be visually presented. Here we will explore the work of students Yujuan Cui and Moeko Doi.

Beginning with prototyping workshops the students Yujuan and Moeko explored, paper modelling and a hidden drawing exercise in which paper was split into four sections where each person took turns drawing their own section of a letter without looking at the previous (figure 10). This resulted in a disjointed letter form that later inspired the student’s alphabet and moving image.

Figure 10. Paper prototypes (left) and letter sections exercise (right) Credit: Yujuan Cui

Across the weeks, focused on layered structures, the students started to explore digital prototyping and how textile layers could be communicated (figure 11). Prior to interim feedback from the BIT researchers, Yujuan and Moeko developed a concept using three layers of engraved Perspex. Each Perspex layer contained shapes which when brought together in a moving image created the typeface (Figure 12). They specifically designed each layer using a different pattern to represent different materials that together became more than the individual parts.

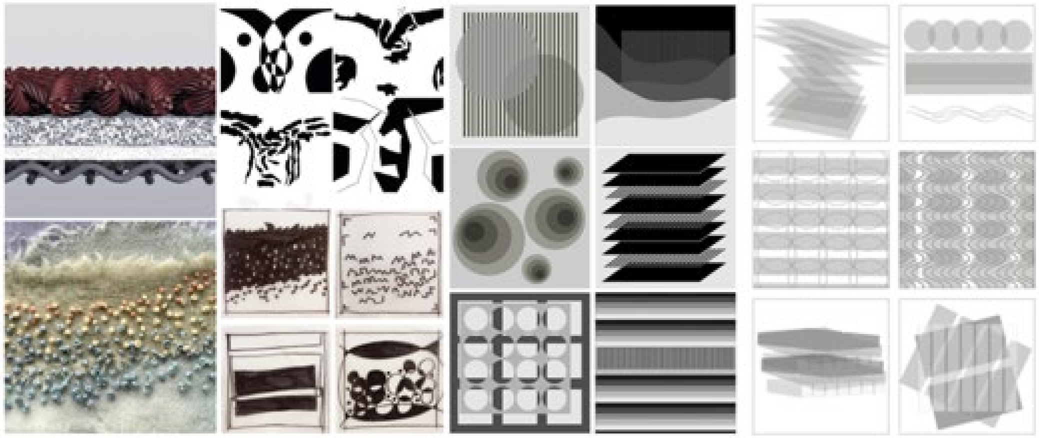


Figure 11. Visual research into the layered structure, Credit: Yujuan Cui and Moeko Doi

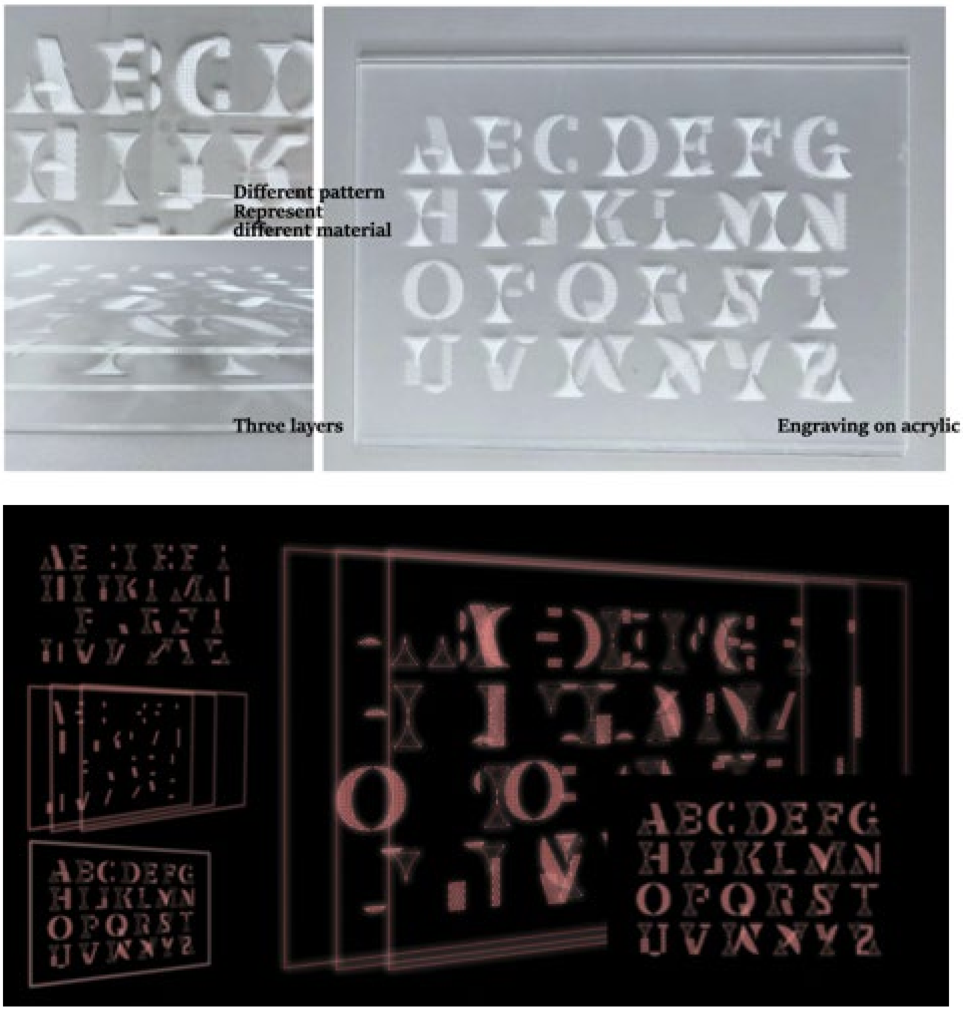


Figure 12. Interim layered concept, Credit: Yujuan Cui and Moeko Doi

The student's moving image also incorporated lights in an attempt to disguise between the layers. The feedback provided by the BIT researchers was to focus on making the visual as relevant to textile designers as possible and expanding away from lighting and into physical materials rather than solely etchings on a single transparent material.

This led to their final moving image design utilising texture, colour and materials in which the word 'layer' appears from the structural layers (figure 13). This was complemented by the students' alphabet design in which they incorporated a similar approach of building different textural components layered one on top of the other to form each letter (figure 14).

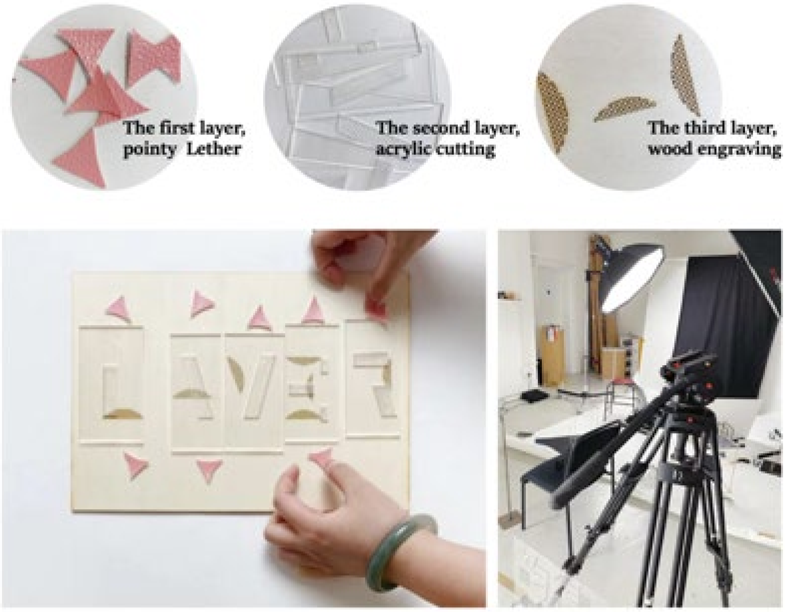


Figure 13. Final moving image design for BIT structure 'layer', Credit: Yujuan Cui and Moeko Doi

Figure 14. Alphabet design based on the BIT structure 'layer', Credit: Yujuan Cui and Moeko Doi

Discussion

This paper argues that the collaboration between the graphic design students, positioned as part of the research (taking a student-as-researcher role) and discussing their interpretations (prototypes) enabled the students to be an integral part of the research process that provided the BIT researchers with clarity and new perspectives on the translation process of material science topics for textile designers. This was demonstrated in the case study (above), in which the graphic students, Yujuan and Moeko, explored the main messaging of the biological structure ‘layer’. The students successfully emphasised, through their physical and digital prototyping, the main message of the structure, namely how using layers provides a different function/property to the final design than those elements alone. This was communicated using different shapes across layers that built a typeface. This visual communication process provided additional clarity for the researchers as they explored the fundamental messages of each structure from Naleway et al.’s (2015) research paper, which later would then be articulated visually and using language for a textile specific audience as part of the official research dissemination.

Furthermore, at the interim stage the BIT researchers provided formative feedback on the work in progress. Yujuan and Moeko’s work used transparent, acrylic sheets to communicate the layer structure. The BIT researchers fed back that they should consider using more textile-like materials to make the communication relevant for the textile design audience. It was here that the researchers started to appreciate the differences between communication to a broader design audience and a textile specific one. This was important translational knowledge produced by the student-as-researcher role that forced the BIT researchers to consider what aspects would make the core messages of the biological structures relevant for textile designers.

These forms of insights occurred across the whole body of students' work. For example, in early prototyping, the students working on the ‘Cellular’ structure began by visualising and prototyping the shapes of plant and human cells (the objects) rather than the 'cellular’ structure themselves. Cellular structures found in nature, such as the honeycomb, demonstrate repeating, geometric, hollow units. The honeycomb is made of wax, a relatively weak material, but the cellular structure used ensures stiffness, even though the majority of the structure is formed of air (the gaps in the cells) which is used to store honey and protect larvae. The lesson from biology, in the case of cellular structures, is the opportunity for designers to create stiffness and volume with a reduced amount of material.

However, the research team observed that the designers tended to focus in on the cell shapes from an aesthetic perspective, rather than the structural lesson of creating varied stiffness and demonstrating high volume using little material. This made the BIT researchers take a renewed perspective on the textile prototypes created in the previous textile-specific collaborators. Their interpretations used textile techniques, which by their nature were 3D. Therefore, even if the textile designers had mistakenly taken inspiration from the aesthetic shape of cells, this could still have been interpreted by the researcher (with expert knowledge) as a volumous cellular structure, when it was in fact just a 3D textile technique being used to articulate their incorrect aesthetic interpretation. Thus, due to the BIT researcher’s expertise, any misunderstanding of the structural lesson would have been missed.

Therefore, the experience of working with visual communication designers generated design knowledge for the BIT researchers in two ways:

- **Clarity** over the key messages needed to translate the biological structures from the material science field for designers.
- **New perspectives** from non-textile designers that highlighted areas of confusion within the BIT framework

Combined, this created new translational knowledge for the researchers about the communication of the biological structures to aid their application into textile design. This demonstrates the role visual communication designers can play in process and the creation of new knowledge within research.

Role of Prototyping

Visual prototyping played an important role in this process. Students used visual prototyping to develop their understanding of the BIT structures, employing the exploratory processes of prototyping, reflection and critique (Poggenhohl, 2018:176) discussed earlier in the paper.

> "We found that using a mechanical hair clip demonstrated what a flower would look like unwound or completely expanded. We began to appreciate how pedal structures can bend and fold to become something functional as a necessity in biodiverse environments."

The different workshops in the project pushed students to use different forms of prototyping - 2D, 3D and 4D. This enabled the process of translation (Ribul & de la Motte, 2018) from the language of material science to the language of visual communication.

> "I understood that the key was to use the minimum amount of material. This means using a minimum of multiple materials to establish the character. For example, ideas such as using holes, reducing the number of lines, cutting the letterforms, etc"

The prototyping processes supported students in generating a 'field of options'. This happened in the context of studio-based workshops which enabled the students to evaluate the prototypes by comparing with others.

> "It was interesting to see how different interpretations collided with each other. Some spirals were flat, some were three-dimensional, and there were helicals viewed from different angles. And I was able to learn from the many directions during the discussions with the group."
>
> "I think it was helpful to see how things we learning were interconnected as a way to strengthen our current research."

The prototypes were presented back to the research team at three points in the process. The prototypes functioned as a 'material conversation' (Poggenhohl, 2018) between the students and researchers, communicating their different interpretations of the research questions. The feedback also focussed the inquiry for both students and researchers. Their interpretations produced communication knowledge by providing non-expert interpretations of the research for discussion and critique. These sessions were the pivotal point in the knowledge exchange between researchers and students that underpinned the student-as-researcher role.

For the researchers, it was at this middle unresolved stage that they gained a real appreciation of the successful translation of key ideas, any confusion created, the red flags for them to resolve and any differences between the translation from non-textile designers and the previous textile centred collaborations. In exchange, this new role for the students introduced them to visual communication design as a method driven by process rather than outcomes. The prototyping that the students created during this project were never intended to be used as final communication of the structures, but rather were part of the research process. The final visual communication, for the dissemination of the project, was completed later but was directly informed by translation knowledge developed in this collaboration.

Furthermore, as a knowledge exchange project, three additional types of knowledge for the students in their new role were established:

1. Better technical understanding of the research to be communicated (the structures and material design concepts).
   Illustrated by a quote from the students working with 'Layer' structure:

   "I had a vague understanding of the structure of a layer, but I think I now have a better understanding of what exactly it is."

2. Improved knowledge about how to design the communication within research context.

   Illustrated by a quote from the students working with 'Overlap' structure:

   "Our typeface aims to replicate how this structure can bend into familiar shapes and how flexible structures, such as those found in nature can overlap and condense into diverse forms. We want to create a structure that can be implemented into a system for typography that demonstrates this flexibility of expanding and contracting."

3. Clearer understanding of benefits of using prototyping to develop communication design within a complex research project.

   "For biotype, the methods we used and why they are effective have provided a framework for how to approach a complex project."

Overall, the process generated important knowledge for both researchers and students-as-researchers on the challenges of communicating research to non-experts, the knowledge this creates about the process and what is important for discipline specific communication. As such, the design process was not just one of traditional problem solving but one that produced *'knowledge useful to those who design*' (Manzini, 2009:5).

Conclusion

This paper set out to explore the role of visual communication design and prototyping within a research context. Conducted through a knowledge exchange collaboration between BIT researchers and visual communication students the project explored how a translation of biological structure design knowledge articulated in the field of material science (Naleway et al., 2015) could be communicated to textile designers for its application across textile design practices. The students working with a live brief, took on a student-as-researcher role and became part of the research process, rather (as is more common) than student-as-professional tasked with finding visual solutions to a problem.

Prototyping (physical and digital) was a key tool used by the students to develop their understanding of the eight biological structure design elements and communicate their interpretations back to the researchers. The overall aim was to understand how translate the knowledge found in the field of material science messages for a textile design audience. The typographical prototypes created were pivotal at the interim stage, a point of connection with the BIT research team, for the students-as-researchers to demonstrate their interpretations and receive feedback. For the BIT researchers working with non-textile designers (after two subsequent textile specific collaborations), these prototypes provided clarity over the key messages and new perspectives that highlighted areas of confusion when translating the biological structures from the material science field for textile designers. This enabled the creation of new translational knowledge for the BIT researchers. In exchange the students gained technical understanding of the research content, improved knowledge of visual communication through prototyping and the methods they can use in the role of students-as-researchers working within a complex research space specifically, as part of the process and in generating translational knowledge.

Ultimately, the research concludes that visual communication designers can play a vital role within a research process. Their methods, such as prototyping, enables the creation of new translational knowledge and its application into design practice.

Acknowledgements

This paper and the research behind it would not have been possible without the support of Prof. Steven Naleway whose paper led to this research. We would also like to thank all the students involved in this collaboration, for the effort and creative work that became part of the research process. Finally, we would like to acknowledge the AHRC for funding this work (grant AH/T006412/1) and the University of the Arts London for hosting the research.

References

Adamson, G. (2007). Thinking through craft. Oxford, UK: Berg.

Barthelat, F., Tang, H., Zavattieri, P., Li, C. and Espinosa, H. (2007) 'On the mechanics of mother-of-pearl: A key feature in the material hierarchical structure', Journal of the Mechanics and Physics of Solids, 55(2), pp. 306–337. Available at: https://doi.org/10.1016/j.jmps.2006.07.00

Bergström, J. et al. 2011. Becoming materials: material forms and forms of practice. Digital Creativity, 21(3), 155-172.

Bio-Inspired Textiles (2022) Layer, Bio-Inspired Textiles. Available at: https://www.bioinspiredtextiles.com/layer-v2 (Accessed: 10 January 2023).

Boyd Davis, S. and Vane, O. (2020) 'Design as Externalization: enabling research', *Information Design Journal, 25(1), pp. 28–42. Available at: https://doi.org/10.1075/idj.25.1.03van*

Carter, R., Day, B., Meggs, P. (2007) Typographic Design: Form and Communication. New Jersey: John Wiley & Sons

Cross, N. (1995). Discovering Design Ability. University of Chicago Press.

Drucker, J. (2014). Graphesis : visual forms of knowledge production. Harvard University Press, Cambridge, Massachusetts.

Frascara, J. (1988). Graphic Design: Fine Art or Social Science? Design Studies, Vol. 5, No.1 (Autumn, 1988), pp. 18-29

Galey A. and Ruecker, S. (2010). How a Prototype Argues. Literary and Linguistic Computing, 25(4):405–424.

Hinrichs, U., Forlini, S., & Moynihan, B. (2018). In defense of sandcastles: research thinking through visualization in digital humanities. Digital Scholarship in the Humanities (DSH), Advance Articles, [fqy051]. https://doi.org/10.1093/llc/fqy051

Johnston, E. (1962). Writing and Illuminating Lettering. London:Sir Isaac Pitman and Sons

Manovich, L. (2007). Q&A Session at the Digital Humanities (DH) 2007 Conference. Urbana-Champaign, IL, June 2007.

Manzini, E. (2015). Design, when everybody designs : an introduction to design for social innovation. The MIT Press, Cambridge, Massachusetts.

Manzini, E (2009). New Design Knowledge. Design Studies, Volume 30, Issue 1, January 2009, Pages 4-12

Morrison, J.E. and Meliza, L.L. (1999) Foundations of the After Action Review Process. IDA/HQ-D2332. INSTITUTE FOR DEFENSE ANALYSES ALEXANDRIA VA. Available at: https://apps.dtic.mil/docs/citations/ADA368651 (Accessed: 14 June 2021).

Motley, P. (2017). Critique and process: Signature pedagogies in the graphic design classroom. Arts & Humanities in Higher Education, Volume 16(3) 229–240

Munzer, T. (2014). Visualisation Analysis and Design. CRC Press.

Norman, Donald A. (1991), "Cognitive artifacts", John M. Carroll (ed), Designing interaction, Cambridge University Press, Cambridge.

O'Leary, D. (1998). Expert System Prototyping as a Research Tool, Applied Expert Systems, E. Turban and P.R. Watkins (Edi), Elsevier Science Publishers

Poggenhohl, S.H. (2018). Design theory to go : connecting 24 brief theories to practice. Ligature Press, Estes Park, Colorado.

Naleway, S.E., Porter, M.M., McKittrick, J. and Meyers, M.A. (2015) 'Structural Design Elements in Biological Materials: Application to Bioinspiration', Advanced Materials, 27(37), pp. 5455–5476. Available at: https://doi.org/10.1002/adma.201502403.

Nelson, R. (2013) Practice As Research in the Arts : Principles, Protocols, Pedagogies, Resistances, Palgrave Macmillan Limited.

Renner, M. (2017). Practice-led Iconic Research: Towards a Research Methodology for

Visual Communication. Visible Language, Volume 51.3 - 52.1, 8–33.

Rittel, H. and Webber, M. (1973). Dilemmas in a General Theory of Planning. Policy Sciences, (4) 155–169 Schön, D. A. (1983) The reflective practitioner: how professionals think in action. London: Temple Smith.

Schubbach, A (2017). Practice-led Iconic Research: Towards a Research Methodology for Visual Communication. Visible Language, Volume 51.3 - 52.1, 34–55.

Shulman, L (2005). Signature pedagogies in the professions. Daedalus 134(3): 53–59

Vaughan, L (Ed). (2020). Practice based design research. Bloomsbury Academic, London, England.

Wragg, N. and Barnes, C. (2016). Graphic Designers' Sense and Knowledge of the User: Is thinking differently the groundwork for acting differently? Visible Language, Volume 50 (No.3), 28-63.

Dr Cathryn Anneka Hall

Cathryn is a postdoctoral researcher at University of Arts London and Design School Kolding currently working on Bio-Inspired Textile research and ReSuit (Recycling Technologies and Sustainable Textile Product Design) research projects respectively. Working at the intersection of academia and industry, Cathryn’s research explores designing for recycling and sorting of post-consumer waste textiles for the circular economy.

Laura Knight

Laura Knight is the Course Leader for the MA Communicating Complexity at Central Saint Martins, University of the Arts London and an Associate Researcher at the Centre for Circular Design. Her research and teaching focuses on visual epistemology and visual innovation in graphical knowledge production.

Prof Veronika Kapsali

Veronika is a Professor of Materials Technology and Design at the London College of Fashion at UAL (University of the Arts London), where she set up and leads the Active Materials Research Lab. Veronika was named ITMA Future Materials INNOVATOR OF THE YEAR in 2014 and more recently was awarded AHRC Leadership Fellow in Bio-informed Textiles in 2020. In the last 5 years she has attracted over £1 million in funding (UKRI/AHRC, Innovate UK, H2020, industry).

Prototyping an employee experience model. A participatory action research project to support organizations in redefining the working routines starting from Employee Experience Design.

Michele Melazzini, Politecnico di Milano, Department of Design, Milan, Italy
Federica Colombo, Politecnico di Milano, Department of Design, Milan, Italy
Gianluca Carella, Politecnico di Milano, Department of Design, Milan, Italy

Abstract

In the post-pandemic context, organizations are facing critical and systemic changes, particularly in people's way of working and related processes. In the last decades, Design and Business Innovation literature presented the different ways Design supports organizations' innovation and transformation processes. This paper starts analyzing experimental approaches - namely *design intervention* - that Design may implement to support organizations in redefining working modes. The focal point of this contribution consists in the redefinition of working routines through the prototype of employee experience models. Furthermore, the existing literature presents a gap in the experimentation and implementation of prototyping activities in the employee experience design. Indeed, the application of service prototyping to employees' experience represents a stimulating challenge among design practitioners and researchers. In a moment of massive uncertainty in knowledge workers' routines, how can Design be applied to Employee Experience to support organizations in redefining working scenarios? More specifically, how may we be able to co-design employee experience through a service prototyping approach?
The theoretical purpose is to reflect on whether implementing service prototyping to employee experience may represent a fertile design research topic. The study presents a qualitative analysis with a Participatory Action Research method, partnering with an Italian bank's HR department and involved employees. Specifically, the paper is built on an experimental project that applies Employee Experience Design and Service Design Prototyping methods to redefine working habits in evolving contexts. Findings show the importance of employee experience prototyping in activating behavioral changes by triggering awareness-raising mechanisms in individuals. Additionally, the lengthy process of changing working practices and routines within organizations can be approached effectively by co-designing employee experience models and iteratively testing and evaluating them. The paper aims to show the potential benefits of exploration for design research in applying prototyping to employee experience design.

Employee Experience; Service Design; Prototyping; Organizational transformation; Co-design

This paper addresses the current role of Design within organizations through *design interventions*: the creative distress that permeates organizational life. Building on recent contributions which reflect on the role of individuals as starting point of organizational change, the study proposes an exemplar of using co-design and service prototyping practices applied to employee experience design. In the knowledge workers' realm, designers recently supported HR in transformation processes, implementing "creative acts of making" (Sanders & Stappers, 2014) to co-design prototypes of employee experience. Thus, the study draws on an experimental project developed by applying Employee Experience Design and Service Design Prototyping methods to redefine working scenarios in uncertain times, like during the COVID-19 pandemic. The research aims are: to reflect on the theoretical implications of an experimental study based on a research and design project developed in a precise context; furthermore, to experiment and co-design service prototypes in unexplored realms, such as the one of employee experience, aiding the changing of working habits and nurturing employee engagement. The paper performs a qualitative analysis with a Participatory Action Research method by testing a prototyped *employee experience model*, co-designed with the partner – a financial institution HR department. Therefore, the prototype developed in the study consists of an *employee experience model*: a set of experiential options that could be freely chosen and navigated by the participants inside the specific context of experimentation. The proposed prototyping framework includes service design elements: tangible touchpoints, spatial configurations, and experience conditions. A significant sample of employees participated in two different iterations of the experimental test of this model to explore how the working experience is changing. The findings highlight the role of the *employee experience model* prototyped: to activate awareness-raising processes in individuals and train them to avoid reintroducing old working routines such as the one adopted before the pandemic. Thus, the *employee experience model* was designed to trigger critical thinking among the organization's people rather than a catalogue of designed workspaces. The different experiential options prototyped can play a crucial role in facing organizations' complex and systemic changes regarding new working life; indeed, co-designing employee experience options– iteratively testing and evaluating them - can represent a practical approach to the lengthy process of changing working habits and routines within organizations. In addition, making employees experiment with a different experience and working model can represent a novel way to enhance knowledge workers' engagement in these critical times.

The paper articulates into four sections. The *background theory* presents the relationship between design, employee experience, and service design prototyping to transform organizations. The *methodology* and *research design* describe how the research was conducted. *Research activities and results* express the diverse areas of inquiry and the primary derived data. Finally, a *discussion* highlights the theoretical and practical implications.

Background theory

Designers are experimenting with practices to face the complexity of the current context, especially in novel and fertile realms for the design discipline. In the last decade, organizations have employed Design approaches and methods - often referred to as "Design Thinking" - to start transforming their structural features and be ready to take the risks that every systemic change entails (Zurlo, 2019).
The adoption of Design within corporations has historically been motivated by strategic factors such as facilitating disruptive innovation pathways or enhancing customer experiences. Lately, the diffused direction has focused on the purposes more oriented to internal cultural growth feeding internal teamwork across the organization silos or changing

internal mindsets and enticing talent (Dunne, 2018). In mature contexts, Design adoption even aims to activate organizational and social transition processes, which can be considered system changes. The advancement of the design discipline and organizational structure are closely linked, according to Buchanan, who stated that "the product to be designed is not an artifact or a customer service anymore but the organization, itself" (Buchanan, 2015).

The *design intervention* mentioned above thus permeates the organizational change actual topics and related literature. Organizational change is the process by which an organization modifies its current structure, **daily working routines**, strategies, or culture in ways that could significantly impact the organization (Herold et al., 2008). Significant organizational change can be planned or unplanned. Planned change happens when a review of business operations identifies issues that must be fixed immediately (Li et al., 2021). Thus, organizations can proactively boost their performance and effectiveness by modifying their business structures and developing new offerings. On the other hand, unplanned change is frequently brought about by unforeseen external forces. The main objective of unplanned change is to maximize potential benefits, reduce the adverse effects of the problematic situation, and turn the crisis into an opportunity (Schermerhorn Jr et al., 2011). Unplanned organizational change, as for the COVID-19 pandemic, can expose employees to uncertainties, leaving them with doubts and concerns that could affect their relationships with the organizations (Li et al., 2021).

The design approaches, *designerly way of organizing* (Zurlo, 2019), have redirected the reflections to the individuals as the starting point of organizational change. Business transformation's drivers are employees’ capabilities, skillsets, and mindset, which are crucial components and indicators of organizational culture (Elsbach & Stigliani, 2018).

Therefore, User Experience Design approaches applied to employees are becoming fundamental for reacting to unplanned changes and activating organizational transformation processes (Auricchio et al., 2018). Indeed, by observing people's needs and behaviors within the organization, design can inspire organizational change. With businesses' increasing need to bring people at the center of organizational transformation projects, the *employee experience design* stands out as an experimental topic for design researchers and professionals. Thus, organizations need to invest the resources necessary to design, produce, and stage an equally unique, memorable, and engaging employee experience if they want to consistently offer value in the area of engagement experience. It is a self-reinforcing cycle with better employee experience resulting in better customer experience, which then feeds back to mankind into more engaging employee experiences possible (Pine II, 2020; Maylett & Wride, 2017). While there is extensive research on customer experience, employee experience has received less attention from both the Business & Innovation management literature body and the Design one (Batat, 2022).

The term "employee experience" was first coined by Abhari et al. (2008); Morgan later provided its conceptualization concerning an organizational and HR perspective (Morgan, 2017). Morgan described the employee's experience as a source of innovation, a way to increase customer satisfaction, and a plan to attract talent, engage them, and boost their performance (Morgan, 2017). Thus, employee experience influences employees’ behaviors and attitudes, impacting organizational performance and well-being (Whitener, 2001; Batat, 2022). Indeed, employee experience is the intersection of employee expectations, needs, and wants and the organizational Design of those expectations, needs, and wants (Morgan, 2017).

In 2022, Batat developed an employee experience theoretical framework (EMX) that combines the different views on the Employee Experience definition, rooted in the organizational and HR management literature; EMX is the employees' personal and changing perceptions of their cognitive, behavioral, and emotional states, as well as their social interactions with other employees, managers, and other internal and external social actors within the employing organization (e.g., suppliers and clients). These perceptions result from various interactions impacting employees' perceived value and well-being throughout their experiential journeys within organizations (Batat, 2022).

Design discipline brings a holistic and experiential view of the employee experience to be extended to what has been named "human experience" (Rossi, 2021): designers have to consider components such as the community, physical workspace, environment, tools, activities, and social platform simultaneously (Lesser, 2016). Therefore, designing Employees' experience means interacting with three spheres: employees' physical environments, their social connections, and the work to be done (Lesser, 2016). Furthermore, applying the User Experience design in the workplace means empathizing with employees as individuals and as a part of representative groups to fulfill experiential needs - cognitive, emotional, social, behavioral, and sensorial (Abhari et al., 2008; Plaskoff, 2017).

Designing employee experience implies looking at the entire experience through the employment lifecycle, a pathway including a multitude of touchpoints - employee interactions, experience with tools, physical spaces, procedures, and policies - as well as interaction with outside sources - conversation with family and friends, former employees, and media reports (Itam & Ghosh, 2020). To provide employees with a comprehensive and tailored experience, organizations must assess and identify the needs of the workers throughout all stages. (Maylett & Wride, 2017).

Organizations adopt design practices to transform processes and outputs of various human-centred activities, including managing human resources (Deserti et al., 2018). The worlds of Design and HR are becoming more and more entwined.

The *employee experience design* serves as the intersection point of these two research areas; thus, this study's theoretical and experimental focus relies on the opportunity to explore this emerging topic. Moreover, the existing literature highlights a gap in the experimentation and implementation of prototyping activities in the employee experience design.

In the professional context, what happens is that designers are asked to participate in the HR transformation process through a variety of co-design activities. In this scope, what plays a crucial role is the implementation of "*creative acts of making"* by designers (Sanders & Stappers, 2014) to co-design and evaluate prototypes. As Sanders and Stappers sustain (2014), through adopting methods for making, professionals can "make things" – as co-designed prototypes - that can activate reflections on future experiences and life habits. Furthermore, employee experience design relates to the practice of service prototyping, intended as a set of approaches and activities aimed at collaboratively representing, communicating, and evaluating design concepts (Blomkvist & Holmlid, 2010). In particular, the challenge in this context consists in how to prototype whole services accurately representing the experience of the future service in a realistic setting.

In the knowledge worker areas, managers frequently ask designers to aid with employee reflection on particular issues and the collective finding of new solutions (Auricchio et al., 2018). Furthermore, managers are experimenting with new leadership approaches based on co-design: they set up their organization's settings to allow everyone to play an active role and maximize their potential. Design is frequently perceived as a catalyst for team building, but the profession's primary objective in this scope has always been to co-design and involve various stakeholders in developing novel solutions to complex issues (Rossi, 2021).

Starting from the explained background theory and observing the significant changes that are occurring in the working habits of office employees the research challenges specific questions: how to apply Design to Employee Experience to support organizations in re-defining working scenarios? How to co-design employee experience through service prototype approach? The research activity presented in the next chapter aims to face the transitions happening in working routines caused by the pandemic.

Methodology

Research Purpose

The research process has a particular experimental design approach, due both to the nature of the experiment and to the specific methodological choice in addressing the identified research questions. The work adopts qualitative and exploratory research methods, to create new knowledge contributions and develop the primary assumption (Creswell et al., 2007).

The concept of prototyping employee experience models to understand - and subsequently define - how working logics are changing is debated by practitioners. However, it is still poorly defined from a scientific point of view. For this reason, and in an effort to be coherent with the complex challenges addressed, the research strategy adopts an explorative approach. Exploratory research does not employ confirmatory mechanisms, as hypothesis. Its aim is to maximise the discovery of generalizations, that lead to the understanding of phenomena through an extensive collection of insights on a specific subject (Stebbins, 2001).

Research Design

The research follows a Participatory Action Research (PAR) methodology, developing, prototyping, and testing new employee experience models with an Italian financial institution, the partner organization in this study. The research project, titled *Working Life Scenario in Evolution* (WLSE), is developed with the organization's HR Department, specifically with the People Development team.
The sample is composed of 38 employees, from three different business units, with diverse job roles and seniority levels.
The research team includes one professor, two researchers and two junior service designers. The project lasts ten months, including the final assessment phase.

Multiple methods of data collection were used and subsequently triabngulated in order to understand partecipant experiences. Due to the COVID-19 pandemic restrictions during the first phases of the research, most data collection tools implemented are digital.

The main tools adopted are semi-structured interviews and individual virtual and in-presence conversations. The team also employed methods inspired by ethnography and digital ethnography research, such as user observation to monitor the testing of the prototyped employee experiences and digital user observation to document routines.

The co-design approach and methods permeate the whole set of research activities implemented with the HR team of the partner organization.

The research process follows the reiterative steps of the PAR approach: Planning, Action, and Reflection, followed by Evaluation (Lewin, 1946; Kindon et al., 2007). Therefore, the research goes through a repetition of these stages until the action is complete. The performed activities follow five steps:

- *Step 1 - Planning – WLSE ideation and definition of LAB 1*: is the planning and structuring of the activities, from the preliminary research to the definition of the employee experience models prototyped in the WLSE Iterative LAB 1. It actively involved the partner organization and its employees both through the exploratory research and the co-design of the LAB. The aim was to collaboratively define and plan the experiment so that it would coherently fit with the study context and address the emerged employees' needs.
- *Step 2 - Action – WLSE Iterative LAB 1*: is the first set of the main experimental activities, specifically the prototyping of employee experience models to co-design and test in a participatory session with the employee of the partner organization.
- *Step 3 – Reflection – redesign: WLSE Iterative LAB 2*: is the analysis of the data collected during the WLS Iterative LAB 1 to generate insights, redesign the employee experience models and prototype them through LAB 2. As in step 1, the partner organization was actively involved to co-design the second iteration of the prototype.
- *Step 4 – Action - WLSE Iterative LAB 2*: it includes the second set of the main experimental activities, specifically the prototyping of employee experience models - redesigned during the previous phase according to the insights gathered through LAB 1 - to test in a participatory session with two other teams of the partner organization.
- *Step 5 – Reflection and Evaluation – prototypes and experiment assessment*: is the activity of assessment of the prototyped employee experience models and of the experimentation and project results. Findings were compared with the framework developed in the previous phases of the research project.

Research activities and results

The research activities included the ideation, prototyping and testing of new employee experience models, through two iterations corresponding to WLSE LAB 1 and WLSE LAB 2. To define and build the prototype, the research team developed a specific framework, that addresses the peculiarities of the prototyping *object* itself: a set of experiential options that could be freely chosen and navigated by the participants, inside the specific context of the bank's headquarters in Milan. Therefore, the prototyping framework includes the prototyping of three service design elements, tightly interconnected: tangible touchpoints, spatial configurations, and experience conditions (fig. 1). The *design intervention* thus consisted of the configuration of spaces, with the prototyping of diverse working environments, each characterized by specific layouts, furniture, and technological tools; and of the design of tangible touchpoints that could stimulate the various working experiences: communication touchpoints, guiding touchpoints. Although various limitations prevented the implementation of major spatial modifications, the research team designed this reconfiguration ad hoc.

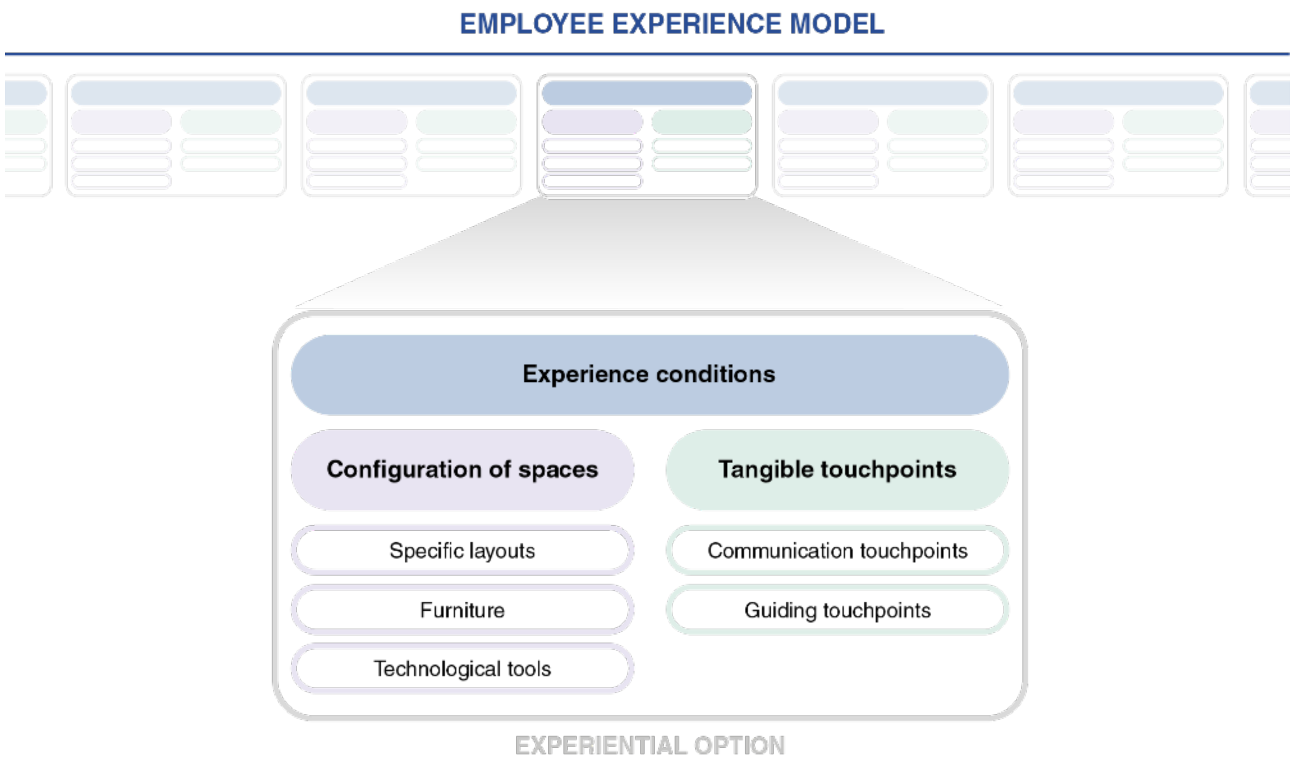


Figure 1: Prototyping framework developed to define and build the prototype

WLSE LAB 1 – first prototype iteration

The ideation of LAB 1 started from the insights gathered through the preliminary research activities (*step 1 – planning*), which explored how to redefine and co-design the employee experience in a post-pandemic scenario within the context of the bank. The aim was to define a collaborative project considering the organization's emerging needs. Therefore, WLSE is an experimental project to orient workers in shaping new work habits by experimenting with novel employee experience models.

The preliminary research included the definition of a set of *personas* representing the recurring professional figures within the organization. These *personas* became the starting point to develop a visual representation of employees' journeys, reproducing a condensed version of a hypothetical working day. The use of this tool allowed to map critical areas and opportunities in the working routines of each employee's profile and guided the definition of a digital conversation format to collect punctual data through semi-structured interviews with the company's key informants, representing the *personas* priorly developed. This phase of digital ethnographic research guided the definition of the urgent topics for the organization's employees to address through the WLSE Iterative LAB 1.

Indeed, the WLSE iterative LAB 1 prototyped a new employee experiences model, following the framework explained in the previous paragraph. To define this new employee experiences model, the research team considered the working framework adopted by the partner company: Activity Based Working (ABW) model. This model aims at giving people autonomy and flexibility in deciding where, when, and how to work. Consequently, workspaces need to adapt to individual needs, offering diverse space options. The bank structures the ABW model around four pillars, referred to work-related areas significant for their businesses. The pillars, named 4Cs, are: Concentration – activities requiring individual focus -; Collaboration – tasks involving team or interdepartmental work -; Communication – activities involving information sharing and conversations between colleagues, not exclusively work-related -; and Contemplation – individuals' needs and time to decompress. Therefore each *experiential option* addressed the activities related to one of the 4Cs - as visible in Figure 2 - to stimulate distinct behaviors, and presented a specific setup to allow employees to test novel working experiences. *Spazio Attivo* and *Spazio Morbido* – two Concentration options – allowed pure operational work and focused and/or private tasks. Collaboration activities – as proactive discussions and collaborative sessions - could be performed in *Spazio Fluido*. *Spazio Raccolto* fostered hybrid Communication – among in-office and remote workers –, while *Spazio Espresso* informal discussions during breaks. Finally, *Spazio Respiro* option addressed the need to decompress from intense working activities.

Figure 2: WLSE Iterative LAB 1, graphic representation of the different employee experience options and related label

As previously explained, the experiential option prototype consists of designing the employees' working experience and related services (experience conditions), the reconfiguration of spaces and a series of tangible touchpoints (communication touchpoints, guiding touchpoints). The *design intervention* on spaces aimed at offering people suitable environments for the working needs addressed by the 4Cs. Communication touchpoints consisted of a Manifesto introducing the whole LAB and posters to briefly describe each working option, to explain their purposes and stimulate participants' reflections. Guiding touchpoints included an explanatory booklet and a leaflet with advice for each employee experience option. Through prototyping spaces and touchpoints, the research team was also able to define and prototype employees' experiences, to be tested by participants.

The testing lasted 3 days, in July 2021 (Step 2 – action), involving 11 people from the Financial Engineering team. During the preliminary onboarding sessions - one dedicated to the team leader and one to the whole team -, the research team introduced the LAB principles and the prototyped employee experience models. In the testing phase, participants could freely use, live, and experiment with the experiences proposed, conducting their regular job activities.

Each day, the research team performed observations, informal conversations with participants and a semi-structured debriefing moment; while an additional debriefing meeting with the team leader and HR members took place one week later. These ethnographic activities allowed to collect data and insights on the prototyped employee experience models, later analyzed by clustering them to identify recurring themes. Specifically, the main topics that emerged were diffusion of the Activity Based Working approach, experience transitions (from one working experience to another and from one working area to another) and spillovers (knowledge and ideas sharing among employees). For each of them, the research team highlighted two types of reflections: cultural awareness insights – theoretical and research-based – and design implications – prototype-oriented. These reflections also allowed to define the significant aspects to address during the LAB redesign (*step 3 – reflection*).

The need to accompany people through new ways of working emerged, to increase cultural awareness on ABW and avoid re-proposing old habits when experiencing new working models.
As a design implication, the need of involving more participants arose, to further diffuse new working models and highlight feedbacks and criticalities about the prototyped employee experience model. Thus, the research team – together with HR people – decided to involve two teams from likewise industries in the LAB 2.

Experience transitions emerged as a critical element: employees should be trained on the importance of moving to different areas according to specific working necessities. The research team planned a training session at the beginning of LAB 2 and a dedicated communication campaign, to stimulate reflection among the participants.
As a design implication, the relevance of distributed privacy areas emerged, allowing employees to individually work without the need to return to their main office and thus facilitating the transitions. This insight was practically translated in the redesign of the experience models prototype of the LAB.

Spillovers and serendipitous contaminations emerged as significant elements of the workplace routine. In-presence working fosters the exchange of ideas and information, as well as the cross-fertilization among different departments and the creation of weak ties (Granovetter, 1973). The decision to involve two teams in the WLSE Iterative LAB 2 allowed to investigate these aspects further.

WLSE LAB 2 – second prototype iteration

The WLSE Iterative LAB 2 prototyped new employee experiences models, responding to the need – emerged from LAB 1 - of transmitting to participants a deeper understanding of the WLSE principles and of raising awareness about the new ways of working. As in the first LAB, the research team followed the prototyping framework priorly depicted.

Also in this LAB, the experiential options followed the 4Cs framework. However, some of the provided employee experience options changed following the insights gathered during the Reflection phase. *Spazio Espresso* became open to employees not taking part in the test, in a highly frequented area. *Punto Ricarica* instead addressed participants' needs of taking a break with colleagues. *Spazio Morbido* left place to more areas dedicated to individual working experiences.

Figure 3: WLSE Iterative LAB 2, graphic representation of the different employee experience models and related label

These changes in the experiential options provided consequently influenced the prototyped spaces and tangible touchpoints. Moreover, their aim changed also to address the identified insights on cultural awareness, stimulating participants' critical thinking on new ways of working and new working habits. Communication touchpoints consisted of a series of posters with triggering questions to foster reflections and raise awareness on ABW and on the new employee experiences among the whole bank division population. Guiding touchpoints included a landing page, providing detailed information about the whole project and the specific employee experience models.

The testing lasted 3 days, in October 2021 (*step 4 – action*). It involved 27 people from two teams belonging to the business areas of BM & HC and Energy. Team leaders participated to an onboarding moment to bring them closer to the LAB purpose, structure and aims. Instead, the whole team engaged in preliminary training, aiming to explain how the ABW, and the new ways of working shaped the LAB 2 definition. As in LAB 1, in the testing phase, participants could freely use, live, and experiment with the employee experience models proposed, conducting their regular job activities.

The research team performed observations and informal conversations with participants on the first day of the test. A semi-structured debriefing moment took place on the final day of the test, involving all the participants. One week after, a debriefing meeting with the team leader and HR members allowed to collect additional insights.

The finale step of the PAR process, the Reflection and Evaluation phase, is presented as a discussion of the research results in the following chapter.

EXPERIENTIAL OPTION - SPAZIO FLUIDO

Figure 4: Visual representation of the experiential option of Spazio Fluido: prototyped spatial configurations (illustration of designed spaces), tangible communication touchpoint (digital version of the printed posters) and experience conditions (photo taken during the WLSE Lab)

Discussion

This paper aims to describe and discuss the practice of service prototyping applied to employee experience design and the roles and implications of these *design interventions* on working routines and habits. The significant number of research activities and data collected and analyzed during the research are synthesized below in a set of key findings.

The study first reflects on the role of *design interventions* in redefining the employee experience and in guiding transformation processes inside organizations: co-designing employee experience models orient and support people to reflect on novel working habits. Avoiding the tendency to reintroduce old working routines, such as the one adopted before the pandemic, is the main challenge for employees. Prototyping and testing employee experience models represent an effective way to train individuals and raise awareness of the new working routines available to them but they have limited impact when it comes to changing employees’ habits. In this sense, the experimentation's initial purpose of changing the employee working routines redirects the focus on activating an awareness-raising process in individuals. Even if, from a theoretical point of view, prototyping can both be implemented with the purpose of designing for and designing with people (Sanders & Stappers, 2014), the findings highlight the effectiveness of co-designing and prototyping employee experience models with the final beneficiaries of the experience. Therefore, making employees experiment with experience models enhance knowledge workers' engagement in these critical times. Thus, the employee experience models were designed and prototyped as a service to trigger critical thinking among the organization's people rather than a catalog of designed workspace.

Therefore, the research project aims to collaboratively engage the employees in the design process by proposing them a set of options through an experience model. In this way, each participant can navigate them according to their personal needs and personally experiment with novel working conditions. This design choice effectively gives the employees the freedom to explore and test different solutions while allowing them to maintain their current working habits. The design of experience "way out" in the prototyped models increasingly helps in making the employees perceive this opportunity.

The crucial contribution of this study is its effort in experimenting with accurately prototyping and then testing the employee experience in an authentic setting. These experiential prototypes can play a key role if implemented by organizations facing complex and systemic changes regarding new working life. Iteratively co-designing, testing, and evaluating employee experience models through prototypes can guide companies in gradually redefining the working logics and adopting new routines. Additionally, the analysis of these findings also highlights how service prototype supports the design research process and the catalytic role that prototyping may have in activating organizational transformation process.

In practice, the developed employee experience prototypes are a combination of different design elements: first, a set of tangible touchpoints – communication and guiding touchpoints -, spatial configurations adapted to the existing physical space – including specific layouts, furniture and technological tools to empower the hybrid interactions - , and then, a series of experience conditions. This combination could serve as an extension of the widely accepted definition of service and experience prototype, which defines it as "the physical environment, the service employees, the service delivery process, fellow customers and back office support" (Zomerdijk & Voss, 2010).

Finally, the study results highlight a set of implications for practitioners. The workplace must deliver value to employees, becoming a place of contamination. Furthermore, the hybrid context influences employees' interpersonal relationships, making them less linear and defined. This change in interpersonal relationships must be considered during the design of employee experience models. Another design implication that emerged concerns experience transitions – changing working needs and settings. When defining hybrid employee experience models, it is critical to consider transitions not only from an individual cognitive point of view but also adopting a systemic approach: practitioners should design experiential conditions that allow a smooth cognitive, physical, and temporal transition.

Finally, it is worth acknowledging the limitations of this study. First, the replicability of the employee experience models proposed should be further verified, understanding how the different organizational context impacts its outcomes. Second, there should be greater understanding of the impact that the time constraints had on the PAR phases of the study: in the project's scope, it is challenging to conduct repetitive verifications and make explorative discoveries capable of grasping potential tangible changes in working routines. Lastly, the subjectivity in the interpretation process is an explicit limitation of this study. That said, the interpretative paradigm is the foundation of the design-based research philosophy.

Despite these limitations, the study puts forward an experimental approach to employee experience design: applying and testing experience and service prototyping practices to face actual challenges in the knowledge workers' realm.

References

Abhari, K., Mat Saad, N., & Haron, M. (2008). Enhancing Service Experience through Understanding Employee Experience Management.

Amis, J., & Greenwood, R. (2020). Organisational change in a (post-) pandemic world: Rediscovering interests and values. Journal of Management Studies. https://doi.org/10.1111/joms.12663

Auricchio, V., Rossi, M., Dezza, G., & Peretti Griva, P. (2018). Service design and human resource consulting: An integrated vision. ServDes. Service Design and Innovation Conference, 401–413.

Batat, W. (2022). The employee experience (EMX) framework for well-being: An agenda for the future. Employee Relations: The International Journal, ahead-of-print.

Blomkvist, J., & Holmlid, S. (2010). Service prototyping according to service design practitioners. Conference Proceedings, ServDes. 2010, Exchanging Knowledge, Linköping, Sweden, 1-3 December 2010, 2, 1–11.

Buchanan, R. (2015). Worlds in the Making: Design, Management, and the Reform of Organizational Culture. She Ji: The Journal of Design, Economics, and Innovation, 1(1), 5–21. https://doi.org/10.1016/j.sheji.2015.09.003

Creswell, J. W., Hanson, W. E., Clark Plano, V. L., & Morales, A. (2007). Qualitative research designs: Selection and implementation. The counseling psychologist, 35(2), 236–264.

Deserti, A., Meroni, A., & Raijmakers, B. (2018). Learning and practicing in service design. ServDes. 2018 Proof of Concept, 1–12.

Dunne, D. (2018). Design Thinking at Work: How Innovative Organizations are Embracing Design. University of Toronto Press.

Elsbach, K. D., & Stigliani, I. (2018). Design Thinking and Organizational Culture: A Review and Framework for Future Research. Journal of Management, 44(6), 2274–2306. https://doi.org/10.1177/0149206317744252

Granovetter, M. S. (1973). The strength of weak ties. American journal of sociology, 78(6), 1360–1380.

Herold, D. M., Fedor, D. B., Caldwell, S., & Liu, Y. (2008). The effects of transformational and change leadership on employees' commitment to a change: A multilevel study. Journal of Applied Psychology, 93, 346–357. https://doi.org/10.1037/0021-9010.93.2.346

Itam, U., & Ghosh, N. (2020). Employee experience management: A new paradigm shift in HR thinking. International Journal of Human Capital and Information Technology Professionals (IJHCITP), 11(2), 39–49.

Julier, G. (2012). Nothing special? (Activist) design skills for the 21st century.

Kelley, T., Kelley, D., & Publishers, H. (2013). Creative Confidence: Unleashing the Creative Potential Within Us All. William Collins.

Kindon, S., Pain, R., & Kesby, M. (2007). Participatory Action Research Approaches and Methods: Connecting People, Participation and Place. Routledge.

Lesser, E. (2016). Designing Employee Experience: How a unifying approach can enhance engagement and productivity. 24.

Lewin, K. (1946). Action Research and Minority Problems. Journal of Social Issues, 2(4), 34–46. https://doi.org/10.1111/j.1540-4560.1946.tb02295.x

Li, J.-Y., Sun, R., Tao, W., & Lee, Y. (2021). Employee coping with organizational change in the face of a pandemic: The role of transparent internal communication. Public Relations Review, 47(1), 101984. https://doi.org/10.1016/j.pubrev.2020.101984

Maylett, T., & Wride, M. (2017). The employee experience: How to attract talent, retain top performers, and drive results. John Wiley & Sons.

Morgan, J. (2017). The employee experience advantage: How to win the war for talent by giving employees the workspaces they want, the tools they need, and a culture they can celebrate. John Wiley & Sons.

Norman, D. A., & Stappers, P. J. (2015). DesignX: Complex Sociotechnical Systems. She Ji: The Journal of Design, Economics, and Innovation, 1(2), 83–106. https://doi.org/10.1016/j.sheji.2016.01.002

Pine II, B. J. (2020). Designing employee experiences to create customer experience value. Strategy & Leadership, 48(6), 21–26. https://doi.org/10.1108/SL-08-2020-0114

Plaskoff, J. (2017). Employee experience: The new human resource management approach. Strategic HR Review, 16(3), 136–141. https://doi.org/10.1108/SHR-12-2016-0108

Pruitt, J., & Grudin, J. (2003). Personas: Practice and theory. Proceedings of the 2003 conference on Designing for user experiences, 1–15. https://doi.org/10.1145/997078.997089

Rossi, M. (2021). Human Resource Design: Steering Human-centered Innovation within Organisations. Springer Nature.

Sanders, E. B.-N., & Stappers, P. J. (2014). Probes, toolkits and prototypes: Three approaches to making in codesigning. CoDesign, 10(1), 5–14.

Schermerhorn Jr, J. R., Osborn, R. N., Uhl-Bien, M., & Hunt, J. G. (2011). Organizational behavior. john wiley & sons.

Stappers, P. J. (2014). Prototypes as a central vein for knowledge development. In Prototype: Design and craft in the 21st century (pp. 85–97). Bloomsbury Academic.

Stebbins, R. A. (2001). Exploratory research in the social sciences (Vol. 48). Sage.

Whitener, E. M. (2001). Do "high commitment" human resource practices affect employee commitment?: A cross-level analysis using hierarchical linear modeling. Journal of Management, 27(5), 515–535. https://doi.org/10.1177/014920630102700502

Zomerdijk, L. G., & Voss, C. A. (2010). Service Design for Experience-Centric Services. Journal of Service Research, 13(1), 67–82. https://doi.org/10.1177/1094670509351960

Zurlo, F. (2019). Designerly Way of Organizing. Il Design dell'Organizzazione Creativa | Designerly Way of Organizing. The Design of Creative Organization. Agathon, 5, 11–20. https://doi.org/10.19229/2464-9309/522019

Michele Melazzini

Michele Melazzini, Ph.D. in Design, is a Researcher at the Department of Design - Politecnico di Milano. The research activity focuses on design's role in the organization, covering strategic design and design management research areas. With a background in product design, Michele built his experience in applying and developing design practices to support cultural transformation and innovation processes. He collaborates on international research projects (Horizon 2020, Interreg, Erasmus+) that deal with Creative Industries, Design Thinking processes applied to SMEs, and Entrepreneurship. Michele has been teaching at the Politecnico di Milano Design School and POLI.Design Consortium in the last years. Michele has started learning and discovering the design culture's soul during a long collaboration with Fondazione Achille Castiglioni.

Federica Colombo

Research Fellow at Politecnico di Milano, Design Department. She is a post-grad in Integrated Product Design at Politecnico di Milano. Her research focuses on how strategic design can support innovation in companies and organizations and on the development of digital services and ecosystems in the education field. She mainly works on applied research, supporting enterprises, financial institutions in the innovation of both their internal organization and customers' offer. Her main research topics are Strategic Design and Service Design. She is teaching and tutoring in courses related to her research topics both in the School of Design of Politecnico di Milano and in the POLI.design Consortium.

Gianluca Carella

PhD candidate with a background in Product Service System Design and Management Engineering. His research is focusing on how design can support companies in creating innovation, understanding how to overcome the barriers that companies may face in adopting design thinking. At the same time, he is working on projects that deal with entrepreneurship, supporting start-ups in combining the design and the business binomial, and understanding the role of design inside technology start-ups. Actually, he is collaborating with the Department of Design of Politecnico di Milano where he is working as designer and researcher involved in European research projects (Horizon 2020, Interreg, Erasmus+). His main streams of research are Design Thinking, Strategic Design, Service Design, Design Management and Entrepreneurship. In the last years, Gianluca is teaching subjects related to his research activity both in the School of Design – Politecnico di Milano and in POLI.Design Consortium

Track 4: Sustainable and Biological solutions

- A Preliminary Investigation into Prototyping for Low Techs.

- Designers prototyping in the lab: Introducing an extracurricular activity exploring bacterial colouring in a design educational setting

- Designing Fungal Kinship: From Material to Co-Creator Through Speculative Prototyping

- Designing matter across scales with microorganisms: The MMMM (Micro-Mezzo-Macro-Meta) approach

- Designing Sustainable and Affordable Smart Home Solutions: The Role of Prototyping

A Preliminary Investigation into Prototyping for Low Techs

Marianna Joy Coulentianos, School of Design and Creative Arts, Loughborough University

Abstract

"Low techs" are technologies aimed at creating deep sustainability, collective resilience, and cultural transformation by adhering to three core requirements: useful, accessible, and durable. Despite the significant effort invested in designing technically feasible low-tech solutions, relatively little research has been conducted on the viability and desirability of these technologies. Current prototyping methodologies support design processes beyond technical feasibility and can be leveraged throughout a design process to support design for viability and desirability.
This paper examines the potential role of prototypes in the development of low techs, drawing upon the existing work of the Low-Tech Lab in conducting and documenting experiments with these technologies. Opportunities for further use of prototyping as a tool to design and develop low techs are identified, and reflections are shared on how low-tech principles might create new avenues for the roles of prototypes.

Low tech; prototyping; sustainability; new prototyping methods

"Low techs" are a set of technologies aiming to create deep sustainability, collective resilience, and cultural transformation, popularised by Bihoux (2014). Low techs achieve three goals: to be useful (e.g., fulfill people's essential needs), to be accessible (e.g., contextually appropriate, locally made with local materials, adapted to local conditions, financially accessible, understandable), and to be durable (e.g., long service life, repairable, reduce negative environmental, social, and societal impacts) (Low-tech Lab, 2022a).

Low techs can help overcome barriers to transitioning towards just and sustainable futures by empowering people and organisations to take ownership of their transition pathways. Low techs can help reduce the cost of living by relying on community ownership; repair networks; and resilient technology catering to basic needs, including housing, heating, food, and energy. For example, low techs are timely with regard to the energy crisis in the UK as many low-tech solutions reduce energy demand, such as passive solar systems, biodigesters, composting systems, and rocket stoves. Such examples of low tech include new technologies and updated historical technologies, and their design and development rely heavily on prototyping and testing. Therefore, understanding how prototyping methods and approaches can enhance the low-tech design process is valuable.

Prototyping is considered a critical activity in new product development (Wall MB et al., 1992). The use of prototypes during a design process has been shown to produce a "greater number of functional ideas that solve the design problem" (Viswanathan et al., 2014). Prototypes are often used throughout a design process to help designers develop requirements, generate concept solutions, communicate ideas to stakeholders, and verify design objectives (Atman and Bursic, 1998; Driessen and Hillebrand, 2013). In the scope of this paper and following the EKSIG 2023 definition of prototypes, we adopted a broad definition of prototypes as “any representation of a design idea regardless of the medium” (Houde and Hill, 1997).

Prototyping methods and processes have been developed to be specific and specialised based on the design discipline (e.g., service prototypes (Blomkvist, 2018)) and the context (e.g., prototyping methods used in cross-cultural design (Coulentianos, 2020)). New contexts of use lead to the creation of new shared language and reflection on prototyping practice. Hence, one might reflect on how low techs, which aim to shift the paradigm of how technology can exist alongside a sustainable and just society, might also shift some prototyping paradigms. This paper describes a preliminary investigation and reflections on how prototyping methods can support the successful development and implementation of low techs and how low techs might provide new avenues for the roles of prototypes.

Contextualising Low Techs

The Low-Tech Lab (LTL), a French organisation founded in 2014 that experiments with low techs, define *low techs* as being inclusive of objects, systems, techniques, services, know-how, practices, ways of life, and schools of thought (Low-tech Lab, 2022). Despite a clear predominance of objects in the low-tech literature, such an inclusive definition discourages an overreliance on technology in the transition to just and sustainable futures. In alignment with this definition, low techs can be, in many cases, product-service systems that aim to change how we use objects and technology, as well as other social institutions, employment, economies, and the commons.

Low techs can be a building block of post-growth futures where humans live within ecological limits. While acknowledging the diversity of degrowth movements, many of them invite a more critical approach when considering the adoption of new technologies (La décroissance et ses déclinaisons, 2022), which takes into account the rebound effect – the effect by which any efficiency increase related to resource exploitation is followed by an increase in the resource utilisation, thereby negating any environmental gains (Meng and Li, 2022; Jevons, 1865). The rebound effect has been consistently observed since the 1860s.

The definition of low techs varies slightly across the literature; some definitions are more prescriptive about what techniques and technology is low tech. According to the *Fabrique Ecologique*, low techs are technologies that are: simple, require the least possible dependence on non-renewable resources, and are accessible to people in terms of cost, maintainability, and repairability (La fabrique écologique, 2019). The founder of the LTL, C. Chatelperron, disagrees with the view that low tech means without transformed materials or modern technologies (Aimé, 2023). The LTL’s approach does not oppose “high tech” but instead invites reflection around the sustainability, accessibility, and repairability of the artefacts we create.

The low-tech principles intersect with other design philosophies, such as the maker space movement, crowd-sourcing, jugaad, and design for development. However, the low-tech principles differentiate themselves in that the primary goal is to help society transition to modest, sustainable futures.

Some criticism of the do-it-yourself movement applies to the low-tech movement, which has tended to focus on projects implemented at the individual or nuclear family level. The idea that one should do everything themself can be counterproductive to creating resilient communities where people develop competencies in specific domains (Vidal, 2017). Is a world without *boulangeries* (French bakeries) where everyone makes their own bread with their solar ovens desirable? To that end, the LTL has been working towards and reporting on the professionalisation of low techs: where organisations, non-profits, and companies can commercialise low techs and provide support in their adoption and diffusion (Low-tech Lab, 2023.b; Low-tech Lab, 2023.c; Low-tech Lab, 2023.d).

Methods

Research question

The present study represents an initial effort to address the research question: How are prototyping methods and processes currently utilised within the low-tech movement?

While the primary focus of this paper is on the research question above, the authors also use the findings to provide preliminary reflections on the potential for further leveraging of prototyping methods and processes in designing low techs and the potential impact of low-tech principles on the roles of prototyping.

Introducing the Low-Tech Lab

The body of work of the LTL was identified as an appropriate body of work to gain insight into the research question. The LTL is a French non-profit organisation started in 2014 and has been experimenting with and documenting the growing low tech movement (Low-tech Lab, 2023.e). As an example of the LTL's work, the *Nomade des Mers* (translation: Nomade of the Sea) project is one of the most notable endeavours. This project involved a crew of several people embarking on a six-year journey aboard a sailboat to meet various actors within the low-tech movement, including those who develop and commercialise low-tech solutions worldwide, and then constructing replicate models for use and study on the sailboat. Another notable project, the *Enquetes du Low-Tech Lab* (translation: Investigations by the Low-Tech Lab), involved conducting investigations and providing reports on the implementation of low-tech solutions in various contexts. A compost-toilet service in an urban environment in France was studied as one of the investigations.

The mission of the LTL is "to make you want to live better with less, thanks to the low-tech spirit!" (Low-tech Lab, 2022.f) To achieve this mission, the LTL conducts a series of explorations (i.e., learning from other actors in the low-tech space); experimentations (i.e., testing things themselves); as well as the management of collaborative tools (e.g., low tech wiki) and community programs. Documentation of the above is at the core of what the LTL does, thereby creating a rich source of information on how low techs are documented, tested, and improved (Chatelperron and Fasciaux N, 2018). The LTL has positioned itself as a synthesiser and diffusion group of all things related to low techs. This position can be understood through their dedication to documenting and publishing their exploratory and experiential work on low techs. Therefore, such documentation was deemed an appropriate place to start investigating the role of prototypes in the low-tech movement.

Document analysis

Table 1 provides a summary of the data collected for the preliminary analysis and the rationale for the selection of these documents. As the LTL is a French organisation, a significant portion of the documentation produced by the organisation is in the French language. The author, a native French speaker, analysed documents in English when available and in French when necessary. In the findings section, specific excerpts have been translated by the author and are identified as such.

Table 1: Documents selected from lowtechlab.org for preliminary analysis (22)

Data	Rational for selection	Description of the data	Associate LTL project	Language
LTL website – all mentions of “prototyp” (Low-tech Lab, 2023.g)	Provides verbatims of the words ‘prototype’ and ‘prototyping’ in use	Excluded the mention “R&D – Prototype”, 30 mentions identified.	Across all projects	French
Nomade des Mers television series (ARTE, 2023)	Narrates in video format the prototyping and testing processes carried out during the project	15 episodes of around 25min each	*Nomade des Mers*	French
Habitat Low-Tech report (Lévêque And Chabot, 2020)	Reports the results of a 1-year pilot test use a low-tech tiny house ‘prototype’	103-page report	*Habitat Low-Tech*	French

Prototyping frameworks

Table 2 presents the prototyping definitions, frameworks, and classifications utilised to decipher the various prototyping practices documented in the LTL documents. These definitions and frameworks were compiled from a review of prototyping literature conducted by the author in 2020 (Coulentianos, 2020). While the review is not intended to be exhaustive, it provides a comprehensive overview of the major themes within the literature on prototyping methodology.

Table 2: Prototyping definitions, frameworks, and classifications. For ease of reporting, the topics identified in the LTL documents are highlighted in grey in the table and are italicized in the results.

Category	Topics	Reference
Prototype definitions		Oxford Dictionary of English (2010)
		Lauff et. al., (2017)
		Otto and Wood, (2000)
		Ulrich and Eppinger, (2011)
		Menold, (2017)
		Houde and Hill, (1997)

Prototyping frameworks	Prototyping strategies	Rodriguez-Calero et. al., (2020)
	Usability testing	Lewis, (2006)
	Roles of prototypes	Lauff et. al., (2017)
	UX prototyping	Coleman and Goodwing, (2017)
	Service prototyping	Blomkvist, (2014)
	Discursive design	Tharp and Tharp, (2022)
	Prototyping for X	Menold, (2017)
	DIY & prototyping	Camburn et. al., (2015)
Prototype classifications	Prototype types	Coulentianos et. al., (2023)
	Pretotyping	Savoia, (2019)
	Prototrials	Jensen et. al., (2017)
	Probes	Sanders and Stappers, (2014)
	Rapid prototyping	Sass et. al., (2006)
	Looks-, behaves-, works-like	Buchenau and Suri, (2000)
	Proof-of- prototypes	Ullman, (2003)
	High/low fidelity	Lim et. al., (2006)
Other prototyping behaviours	Fixation	Viswanathan et. al., (2014)
	Novice vs experts	Deininger et. al., (2017)

Reporting of results

The present study serves as an initial investigation into the use of prototypes within the context of low techs. Based on a preliminary analysis of a subset of relevant documentation, this research aims to extract examples demonstrating how various prototyping methods are discussed in developing low-tech technologies. The following section, "Findings and Discussion," presents extracts from the LTL documentation and relates them to the definitions, frameworks, and classifications of prototyping identified in the methods section. The utilisation of various prototyping methods is evaluated, and suggestions for potential improvements in their application are offered.

Findings and discussion

Prototyping of low techs fits with conventional definitions of prototyping

What does the LTL call 'prototype'?

The Oxford Dictionary proposes the following definition of a prototype: "*A first, typical or preliminary model of something, especially a machine, from which other forms are developed or copied.*" (Stevenson, 2018) The idea that a prototype is a 'first of something' can be found in the way the word 'prototype' is used on the LTL website, as seen below.

“We made a first prototype of a manual compost grinder to save space and facilitate the digestion of the larvae.” [translated] Project *Nomade des Mers*

Lauff et al., 2017, describe a prototype as a physical embodiment of critical elements of the design and an iterative tool to enhance and inform decision-making throughout a design process (Lauff et al., 2018). The LTL website has several mentions of iteration jointly with the word “prototype”, as seen below with the mention of ‘improvements’ and of a ‘second’ prototype created.

“*As you can imagine, the first prototype was very rickety… But it helped us see the enormous potential of these pedal machines! From improvements to improvements, we perfected our grain mill, and a multitude of other machines followed*.” [translated] Mario Juarez, Maya Pedal association

“The improvement of prototypes of low-techs, particularly around solar lamps.” [translated] Low-Tech Lab Yaoundé

“a second boat prototype made 100% from composite reinforced with natural jute fibres, the famous Gold of Bengal” Project Gold of Bengal

Otto and Wood define a prototype as *“a physical instantiation of a product, meant to be used to help resolve one or more issues during product development”* (28). The idea that prototypes are meant to be tested is present throughout the LTL website, as experimentation with low techs is at the core of what the organisation does.

“We made a first prototype of a reflector oven with an adhesive mirror. Our first cooking tests were a success.” [translated] Project *Nomade des Mers*

Ulrich and Eppinger define a prototype as *“an approximation of the product along one or more dimensions of interest”* (Ulrich KT, Eppinger, 2011). These dimensions of interest include the *“physical to analytical”* spectrum and *“comprehensive to focused”* spectrum. The LTL website has several mentions of prototypes as ‘comprehensive physical’ approximations of the ‘product’, describing fully functioning systems that are then ‘piloted’ over several months, as seen in the examples below.

“A prototype of [a biosphere for low impact living] that meets vital human needs” [translated] Project Biosphere 1

“The Habitat Low-Tech project, a prototype of an autonomous low-tech house (...) [in which two members of the LTL will] act as a resident guinea-pig for one year and measure the economic, ecological and ergonomic impact of low-tech in a Western context.” [translated] Project ‘Low-Tech Housing’

“Building a vehicle prototype (a true low-tech concept car!) and creating a large expedition on board [the prototype]” [translated] Project Agami

Preliminary findings show that some prototyping efforts go beyond prototyping objects and extend into the *services* realm, as described in the example below of a ‘public’ service prototyped in Benin.

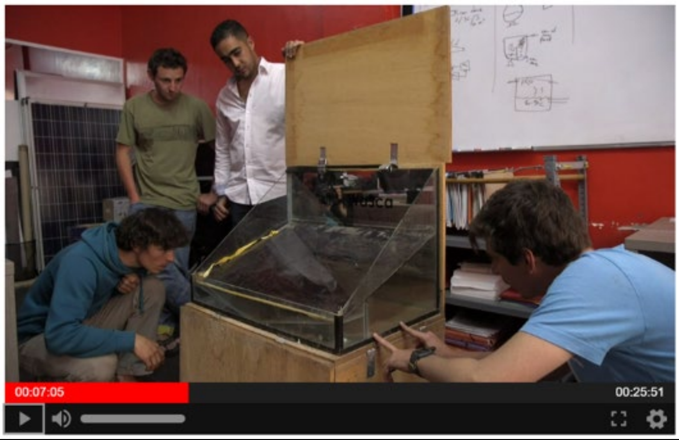
“Building of public dry toilets for a community of 2000 people. The project is based in Benin (west Africa) and is a prototype to be duplicated in other cities in Benin” [translated] Association pour le Developpement de la Commune de Savalou

Hence, prototyping tools and methods from *service design* and the growing work on product-service systems could be valuable to the design of low techs. As seen in all the examples in this sub-section, prototypes of low techs are discussed on the LTL website in ways that fit conventional definitions of prototyping.

A deep dive into an example prototyping process aboard the Nomade de Mers

To better understand what processes may look like when prototyping low techs, an in-depth example of a prototyping process is presented below from the *Nomade des Mers* television series, aired on Arte in 2018. Each series episode followed the crew in a new coastal city while they discovered, built, and tested a new low tech (ARTE, 2023). The episodes were generally very focused on the technical aspects of construction and testing of the low techs. In Table 3, we synthesise several prototypes presented in episode 2 (working with Medhi Berrada, Founder of Alto-Solutions, Morocco), during which the crew tested low tech desalination systems. The prototyping process presented in the episode is summarized below.

Table 3: Synthesis of prototyping activities presented in Nomade des Mers, les escales de l'innovation - Episode 2

Illustration	Step description
	**Step 1.** A “first prototype” of a desalinator tested the functionality of the design. It enabled the diagnosis that too much air between the water and condensation surfaces hinders the device’s efficiency. The learnings prompted a new design idea.
	**Step 2.** Three prototypes to assess the new idea before finalising the design: a reproduction of a widely disseminated model (schematics found online); the implementation of the new design idea; a proposed further improvement on the new design idea. All three prototypes were built with readily available and repurposed materials (e.g., foam fish basins, aluminium foil, PVC pipes). They were even built with low-tech production methods such as the pedal-powered drill. The prototypes showed that the new design idea significantly increased the desalinator's performance.

	**Step 3.** A cardboard prototype is made to engage the final system's manufacturer: this prototype is not explicitly named as such. The crew explained the basic design using the cardboard prototype and mentioned they wanted it bigger and made of clay. The manufacturer explained that the dimensions requested were impossible to make. He proposed a different way of manufacturing the system with a rounded design for more robustness (made from a single piece of clay rather than several pieces assembled, creating weak points at the joints).
	**Step 4.** The results from the final prototype made with clay pieces were disappointing as the yield was lower than anticipated. The decision to use clay as a material is questioned. **Reflections on the prototyping process:** A crew member mentions that it being their first stop, their prototyping and testing skills need to be better developed and that they hope to improve. The final prototype will travel on the boat, and the crew hope to keep iterating on its design as they spend more time using it.

In the description of the prototyping process above, the author identified iterative *low-fidelity functional* prototypes made from *free-form* and *constrained* repurposed materials. Each prototype had its primary function tested against efficiency criteria: how much water it can desalinate. The strategies of *creating and testing multiple prototypes concurrently*, *all at the same level of refinement*, were leveraged and enabled the selection of the most efficient system. When engaging the *manufacturer* of the final refined prototype, the crew brought a non-*functional cardboard mock-up* of the design to be handmade out of clay. The prototype is used as a basis for a conversation, creating a shared understanding between stakeholders. An *integrated functional prototype* with parts manufactured by a specialist was then created and tested.

The prototypes described in Table 3, Step 2 were fabricated using repurposed materials, which are commonly utilised in constructing low-tech devices as outlined in the literature on LTL tutorials. As a result, the distinction between a prototype and a final product becomes ambiguous, particularly in instances where mass production of the latter is not intended. The examination of prototyping approaches within the realm of Do-It-Yourself (DIY) has led to the identification of specific prototyping principles within this space, where the design and fabrication of a commercial artefact is not always the primary objective (e.g., the modification of existing products) (Camburn et al., 2015). It is possible to establish a parallel between the concepts of “DIY” and “low tech” and to postulate that novel prototyping methods and perspectives may be discovered within the realm of low tech.

Additionally, the methods and tools employed for creating the prototypes depicted in Table 3 align with low-tech principles, such as the pedal-powered drill and handmade clay parts. This example brings forth the concept of "low-tech prototyping," a term commonly used to denote prototyping methods, such as paper prototyping, that do not involve high-tech tools or rapid manufacturing methods. Furthermore, it raises the question of whether prototyping in the context of low-tech systems excludes the possibility of creating complex prototypes with sensors, processors, and connected devices, as described in the EKSIG2023 introduction. This question is particularly relevant given that several criteria of low-tech systems, as outlined in reference (Martin and Gaultier), pertain to questioning dominant technical and social practices and tend towards increasing autonomy and emancipation by decreasing reliance on automation. In this context, the Habitat Low Tech project report includes reflections on how photovoltaic solar panels may not be considered low-tech. Therefore, it is paramount to consider the potential role, if any, of "high-tech" prototyping within the development of low-technology systems.

Lastly, the case of the cardboard mock-up stands out. The mock-up is not described as a prototype in the episode, despite its central role in creating a shared understanding between the manufacturer and the designers. While applying prototyping methods and processes to develop functional prototypes is at the core of the LTL documentation, we have here an example of a non-functional prototype used to communicate between a project's stakeholders. The implementation of non-functional prototypes can also provide a multitude of benefits (35). In the following section, we shall delve deeper into the methodologies for prototyping low-techs that do not solely focus on functional feasibility.

Prototyping low techs beyond object functionality

Demonstration prototypes

Meyer, 2020, observes that the LTL puts much effort into demonstrating low techs, showcasing moments in the *Nomade des Mers* television series where the crew is enthusiastic about showing 'what is possible' (Meyer, 2022). The below quote further illustrates how many of the prototypes created are purposefully destined to be demonstration prototypes, per the mission of the LTL.

"A future vehicle prototype, demonstrating a possible rethinking of usage patterns and processes" [translated] Project Agami

The Low-Tech Lab festival held in the summer of 2022 in Concarneau (Low-tech Lab.h, 2023) aimed to hold a space where low techs were showcased, demonstrated, and discussed. The festival included exhibitions, visits to the *Habitat Low-Tech* tiny house and *Nomade des Mers* laboratory boat and all their embarked low techs, other associations were invited to demonstrate their low techs, and conferences discussed the relevance of low techs in various contexts. Many low techs 'prototyped' and tested over the years were showcased, becoming demonstration prototypes. In addition, the whole festival relied on low techs to function (e.g., from compost toilets to solar systems to generate electricity to low-tech stoves used to cook food to feed the volunteers throughout the week). The festival itself demonstrated how low techs could be used successfully.

According to work by Martin and Colin, 2021, who mapped eight main principles of low techs, psychological transformation is one of the significant aims of low techs (Martin and Colin, 2021). Low techs help create new imagined possibilities for what the world could look like, and prototypes can help. Projects such as Biosphere 1 and 2, *Nomade des Mers*, *Habitat Low-Tech*, and the Low-Tech festival are future-facing projects meant to be ephemeral while defying the status quo and bringing people together around new possible futures: the festival drew 15,000 people to Concarneau, France, over one week.

Usability testing, ergonomics, and emotional evaluation

Little consideration for usability and ergonomics emerged in the "*Habitat Low-Tech*" project documentation. The report published on the project explains that the year-long pilot experiment, during which two members of the LTL were to live in the tiny house using around 20 low techs in their everyday life, had the goal of going beyond a purely technical study of the low techs to include an evaluation of their "quality of life" (Lévêque and Chabot, 2020). The report, therefore, discusses usability aspects such as comfort and ergonomics. While these evaluations are not generalisable (as stated in the report), they show a first concern for the desirability of low techs, which is investigated using prototypes in a pilot experiment format.

Beyond usability and ergonomics, the authors of the *Habitat Low-Tech* report also report their emotional experience throughout the experiment. They discuss feelings such as satisfaction of understanding and having control over their electricity supply, the gamified experience of handling a limited energy stock p.48, "a funny feeling of mental relief" [translated] p.91, and feelings of safety p.92 and calm p.94. The report's authors end with a positive note about the joys of participating in the experiment. Hence, some value was placed on user experience testing with prototypes.

Prototyping tutorials, fabrication, maintenance, and repair

Low techs are defined by the fact that they are technologies people can appropriate by directly fabricating and repairing them themselves. Therefore, low techs rely on tutorials, workshops, and other forms of information exchange to make the technology accessible in manufacturing, maintenance, and repair. The LTL has developed rich networking and diffusion tools, which include the wiki, which gathers over 200 tutorials and the directory of low-tech actors. On the LTL website, one can answer the question: *What low techs are near me?* Beyond managing the wiki, the LTL has also published the "Tuto des tutos", a tutorial on how to make a tutorial.

In the current analysis, a need for established prototyping methodologies specifically tailored to the areas of tutorials, fabrication, maintenance, and repair was identified. Additionally, the author's experience suggests that, despite the potential benefits, the application of prototyping strategies is seldom extended to the early identification and mitigation of implementation factor hurdles such as shipping, shelving, instruction manuals, maintenance, and repair. The potential advantages of utilising prototyping approaches in the creation of tutorials, the testing and iteration of materials and fabrication processes in various contexts, and the design for maintainability and repairability, particularly given the importance of these characteristics in low-tech products, warrant further investigation. Furthermore, the stakeholders involved in low-tech products may differ from those typically involved in prototyping processes (Coulentianos, 2022). As such, the question arises as to whether new prototyping methodologies are needed to achieve these design goals and how the DIY and maker movements and the field of design for customisation can inform the prototyping of low-tech products.

It has been identified that one of the key principles of low-tech design is the interrogation of design methods and practices (Martin and Gaultier). One of the ways in which low-tech design challenges traditional design practices is by prioritising accessibility in fabrication, maintainability, and repairability, which raises the question of how design principles may shift when these requirements are placed at the forefront. In the context of prototyping, it is worth considering the potential implications of this shift. For example, a new form of prototyping for low techs could be imagined, one that is the inverse of “Wizard of Oz” prototyping, where the goal is to reveal the inner workings of a product entirely rather than conceal them. Consequently, the exploration of prototyping techniques tailored explicitly to low techs has the potential to bring about a paradigm shift in the methods and processes of prototyping.

Lastly, another deviation from traditional prototyping approaches that may arise in the context of prototyping low techs is the rejection of seamlessness. While conventional prototyping methods aim to identify and rectify user errors in order to create a seamless final design, following the low-tech principle of psychological transformation (Martin and Gaultier) may instead lead to the creation of prototypes that incorporate discursive design principles, highlighting the often hidden, complex, and environmentally taxing moments of everyday life, such as turning a car on. Could one of the dimensions of prototyping low techs follow in the footsteps of the bicycle connected to a toaster to make tangible the amount of human power needed to make toast (Olympic Cyclist Vs. Toaster, 2015)?

Conclusion

This study identified various prototyping approaches implemented in the context of design and development of low techs, as reported in the LTL available online documentation. Multimedia files documenting several projects undertaken by the LTL were used in the analysis. Suggestions for potential improvements in using prototyping approaches in the design of low techs were discussed following each finding.

Several conventional definitions of prototyping aligned with how the word “prototype” was used on the LTL website. Some prototyping efforts also seem to go beyond prototyping objects and extend into services. Hence our findings suggest that prototyping tools and methods from service design and the growing work on product-service systems could be valuable to the design of low techs.

Several examples of prototyping strategies were identified, providing evidence that methodological approaches aligned with prototyping literature are used for prototyping low techs, even when those were not explicitly named as prototypes or prototyping methods. A parallel was drawn between low techs and the DIY movement, where the distinction between prototype and final artefact faded. The parallel carries further, and we might postulate that novel prototyping methods and perspectives may be discovered within the field of low techs. The methods for making prototypes were also observed as being in themselves low-tech, thereby questioning the potential role, if any, of “high-tech” prototyping within the development of low-technology systems.

Looking beyond functional prototyping, the following areas of prototyping were identified as areas where prototyping could further benefit the design of low techs and where it is possibly underutilised: demonstration prototypes to invite new imaginaries and psychological transformation; usability, ergonomics, and user experience testing; prototyping for development of tutorials, fabrications processes, maintenance and repair processes.

Parallel to identifying opportunities for prototyping to further contribute to the low-tech movement, opportunities for the low-tech movement to lead to the creation of new prototyping methods and processes was also proposed. The shift away from conventional prototyping could be led by the principle of honesty, where low techs reveal the inner workings of artefacts to stakeholders, and on the objective of low techs to interrupt seamless activities of everyday life to reveal their ecological impact.

These results contribute to the developing body of literature that recognises low techs' unique requirements and design constraints.

What role for designers in the low-tech movement?

Much of the documentation focuses on the technical feasibility of low techs, with little consideration of the viability and desirability factor of such technologies other than the demonstration and usability prototypes presented in the results. A comparison may be drawn with bodies of work, such as the clean cooking initiatives, that have been building new and improved cookstoves for decades. Much time and effort were devoted to making stoves that achieved the technical goals of being more efficient and producing less smoke. However, very few stoves were adopted and managed to displace traditional biomass cooking (Georg and Jones, 2016; Malakar et al, 2018). Criticism of how the work was undertaken includes a lack of human-centred design and a lack of 'designing with' (rather than designing for). The design discipline has been recognised as adding key methods, values, and know-how to designing inclusive technology that focuses on people's needs (Diagnestya and Yap, 2020).

The approach of the LTL could be driven by the fact that many of the founding members are engineers and by the pervasive perception that functionality comes first, before considerations of viability and desirability, despite the latter considerations being essential considerations in adoption pathways and can benefit the creative solving problem process. Designers, therefore, have a lot to contribute to the low-tech movement.

A co-founder of the LTL recognised the need to improve prototypes of low techs in terms of ergonomics and aesthetics (Nahmias, 2019). The work by Martin and Colin, 2021, documents dozens of usability requirements for low techs (e.g., compatibility with existing systems, access to information) based on survey responses (Martin and Colin, 2021) and gives designers an indication of where their human-centred skills could be leveraged.

Limitations and future work

A limited part of the available documentation was analysed for this paper by a single researcher. Therefore, no conclusions can yet be drawn about the presence or absence of certain prototype types in the body of published work of the LTL. The author intends further to analyse the work with a second qualitative coder to establish a robust deductive codebook based on prototyping frameworks and establish inter-rater reliability when reporting further results.

Other reasons some prototype types may not appear in the LTL documentation could be that prototyping activities are not reported in the documentation because they are not seen as valuable to report; the prototype methods are not in use because they are irrelevant. To remediate these limitations, future work could include interviews with people directly involved in the documented projects, their inclusion in the analysis process, and observations of ongoing low-tech projects. Furthermore, more diverse documentation on low-tech experimentation could be gathered for analysis beyond the body of work of the LTL.

Based on this preliminary analysis, a further selection of documents that seem most promising in reporting aspects related to prototyping to analyse will be carried out, and additional types of data gathering will be planned. Specifically, the authors hope to gather data throughout the LTL project accompanying 20 organisations in their sustainable transition efforts by transitioning to and implementing low techs in their core business and operations (Low-tech Lab.d).

References

Aimé A. L'aventure low-tech - Inexploré digital [Internet]. Inexploré. [cited 2023 Jan 26]. Available from: http://inrees-inexplore-preprod.yoursp.in/articles/l-aventure-low-tech

ARTE. *Nomade des Mers*, les escales de l'innovation [Internet]. ARTE Boutique - Films et séries en VOD, DVD, location VOD, documentaires, spectacles, Blu-ray, livres et BD. [cited 2023 Jan 26]. Available from: https://boutique.arte.tv/detail/Nomade_des_mers

Atman CJ, Bursic KM. Verbal Protocol Analysis as a Method to Document Engineering Student Design. Journal of Engineering Education. 1998;87:121–32.

Bihouix P. The Age of Low Tech: Towards a Technologically Sustainable Civilization. Policy Press; 2020. 198 p.

Blomkvist J. Representing Future Situations of Service : Prototyping in Service Design. 2014 [cited 2018 Dec 5]; Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-105499

Buchenau M, Suri JF. Experience Prototyping. In: Conference on Designing interactive systems: processes, practices, methods, and techniques. ACM; 2000. p. 424–33.

Camburn B, Dunlap B, Gurjar T, Hamon C, Green M, Jensen D, et al. A Systematic Method for Design Prototyping. Journal of Mechanical Design, Transactions of the ASME. 2015 Aug;137(8).

Camburn BA, Sng KH, Perez KB, Otto K, Wood KL, Jensen D, et al. The Way Makers Prototype: Principles of DIY Design. In: Volume 7: 27th International Conference on Design Theory and Methodology [Internet]. Boston, Massachusetts, USA: American Society of Mechanical Engineers; 2015 [cited 2022 Dec 15]. p. V007T06A004. Available from: https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings/IDETC-CIE2015/57175/Boston,%20Massachusetts,%20USA/257701

Coleman B, Goodwin D. Designing UX: Prototyping. SitePoint Pty. Limited; 2017. 198 p.

Chatelperron C de, Fasciaux N. *Nomade des Mers*: Le tour du monde des innovations low-tech. Vanves Issy-les-Moulineaux: EPA; 2018. 256 p.

contributeur. Vers des technologies sobres et résilientes - Pourquoi et comment développer l'innovation 'low-tech' ? [Internet]. La fabrique écologique. 2019 [cited 2022 Jul 6]. Available from: https://www.lafabriqueecologique.fr/vers-des-technologies-sobres-et-resilientes-pourquoi-et-comment-developper-linnovation-low-tech/

Coulentianos M. The Use of Prototypes to Engage Stakeholders in Low- and Middle-Income Countries During the Early Phases of Design [Internet] [Thesis]. 2020 [cited 2023 Jan 27]. Available from: http://deepblue.lib.umich.edu/handle/2027.42/162996

Coulentianos MJ, Rodriguez-Calero I, Daly SR, Sienko KH. Global health front-end medical device design: using prototypes to engage stakeholders. Development Engineering. 2020;5:100055.

Coulentianos MJ, Rodriguez-Calero I, Daly SR, Burridge J, Sienko KH. Stakeholders, Prototypes, and Settings of Front-End Medical Device Design Activities. Journal of Medical Devices. 2022 May 18;16(3):031010.

Deininger, M., Daly, S. R., Sienko, K. H., Lee, J. C. Novice designers' use of prototypes in engineering design. Design Studies. 2017;51:25–65.

Diagnestya T, Yap JCW. Sustainable Cooking: Beyond the Cooking Problem with the Lens of Human-Centred Design. In: Gandhi O, Srinivasan D, editors. Sustainable Energy Solutions for Remote Areas in the Tropics [Internet]. Cham: Springer International Publishing; 2020 [cited 2021 Mar 15]. p. 11–30. (Green Energy and Technology). Available from: https://doi.org/10.1007/978-3-030-41952-3_2

Driessen PH, Hillebrand B. Integrating Multiple Stakeholder Issues in New Product Development: An Exploration. Journal of Product Innovation Management. 2013 Mar;30(2):364–79.

Georg WS, Jones PH. What Is a Sustainable Innovation? Cultural and Contextual Discoveries in the Social Ecology of Cooking in an African Slum. Ethnographic Praxis in Industry Conference Proceedings. 2016;2016(1):235–48.

Houde S, Hill C. What do prototypes prototype. Handbook of human-computer interaction. 1997;2:367–81.

Jensen MB, Elverum CW, Steinert M. Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. Design Studies. 2017 Mar 1;49:1–31.

Jevons WS. 'The coal question: Can Britain survive.' First published in 914 (1865). 914th ed. 1865.

La décroissance et ses déclinaisons [Internet]. [cited 2022 Dec 7]. Available from: http://www.editions-utopia.org/2022/05/12/la-decroissance-et-ses-declinaisons/

Lauff C, Kotys-Schwartz D, Rentschler ME. What is a Prototype?: Emergent Roles of Prototypes From Empirical Work in Three Diverse Companies. In: Volume 7: 29th International Conference on Design Theory and Methodology [Internet]. Cleveland, Ohio, USA: ASME; 2017 [cited 2018 Oct 4]. p. V007T06A033. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?doi=10.1115/DETC2017-67173

LÉVÊQUE PA, CHABOT C. Habitat Low Tech. Présentation. Low Tech Lab; 2020.

Lewis JR. Usability Testing. In: Salvendy G, editor. Handbook of Human Factors and Ergonomics [Internet]. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2006 [cited 2017 May 18]. p. 1275–316. Available from: http://doi.wiley.com/10.1002/0470048204.ch49

Lim Y kyung, Pangam A, Periyasami S, Aneja S. Comparative analysis of high- and low-fidelity prototypes for more valid usability evaluations of mobile devices. In: Proceedings of the 4th Nordic conference on Human-computer interaction changing roles - NordiCHI '06 [Internet]. Oslo, Norway: ACM Press; 2006 [cited 2019 Dec 19]. p. 291–300. Available from: http://portal.acm.org/citation.cfm?doid=1182475.1182506

Low-tech Lab, 2022.a – Les Low-tech : l'innovation utile, accessible et durable. [Internet]. [cited 2022 Jul 6]. Available from: https://lowtechlab.org/fr/la-low-tech

Low-tech Lab, 2023.b – Low-tech near you [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/en/tools/initiatives

Low-tech Lab, 2023.c – Les enquêtes du Low-tech Lab, penser et explorer la low-tech à l'échelle des organisations / 2020 - 2022 [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/fr/le-low-tech-lab/les-actions/les-enquetes-du-low-tech-lab

Low-tech Lab, 2023.d – [EN COURS] Expérimentation de la démarche low-tech en Cornouaille / 2022-2023 [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/fr/le-low-tech-lab/les-actions/territoire-low-tech

Low-tech Lab, 2023.e – Who we are [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/en/the-low-tech-lab/presentation

Low-tech Lab, 2023.f – Home [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/en

Low-tech Lab, 2023.g – Accueil [Internet]. [cited 2022 Jul 6]. Available from: https://lowtechlab.org/fr

Low-tech Lab 2023.h – Le festival, kesako ? [Internet]. [cited 2023 Jan 26]. Available from: https://lowtechlab.org/en/festival-2022/le-festival-kesako

Malakar Y, Greig C, van de Fliert E. Resistance in rejecting solid fuels: Beyond availability and adoption in the structural dominations of cooking practices in rural India. Energy Research & Social Science. 2018 Dec 1;46:225–35.

Martin A, Gaultier A. Cartographie du concept low-tech : guider la conception vers des techniques soutenables.

Martin A, Colin C. Ergonomie et low-tech. Représentations et attitudes vis-à-vis du low-tech. Intention d'utilisation et problemes perocus pour 10 low-techs. [Internet]. Low-tech Lab; 2021 [cited 2023 Jan 27]. Available from: https://lowtechlab.org/media/pages/actualites-blog/ergonomie-et-low-tech/6a9b22edbd-1635865837/ergonomie-et-low-tech-contenu_compressed.pdf

Meng M, Li X. Evaluating the direct rebound effect of electricity consumption: An empirical analysis of the provincial level in China. Energy. 2022 Jan 15;239:122135.

Menold J. Prototype for X (PFX): A Prototyping Framework to Support Product Design. Pennsylvania State University; 2017. book.

Meyer M. Expérimenter et rendre désirables les low tech. Une pragmatique de la documentation. Réseaux. 2022;235(5):219–49.

Nahmias M. Système D comme désirable. 2019;hors-série(HS6):38–41.

Olympic Cyclist Vs. Toaster: Can He Power It? [Internet]. 2015 [cited 2023 Jan 27]. Available from: https://www.youtube.com/watch?v=S4O5voOCqAQ

Otto K, Wood K. Product Design: Techniques in Reverse Engineering and New Product Development. 1 edition. Upper Saddle River: Pearson; 2000. 1104 p.

Sanders EBN, Stappers PJ. Probes, toolkits and prototypes: three approaches to making in codesigning. CoDesign. 2014 Jan 2;10(1):5–14.

Sass L, Oxman R. Materializing design: the implications of rapid prototyping in digital design. Design Studies. 2006 May 1;27(3):325–55.

Savoia A. The Right It: Why So Many Ideas Fail and How to Make Sure Yours Succeed. HarperCollins; 2019. 294 p.

Stevenson A, editor. Oxford Dictionary of English [Internet]. Oxford University Press; 2010 [cited 2018 Nov 21]. Available from: http://www.oxfordreference.com/view/10.1093/acref/9780199571123.001.0001/acref-9780199571123

Tharp BM, Tharp SM. Discursive Design: Critical, Speculative, and Alternative Things. MIT Press; 2022. 641 p.

Ullman DG. The Mechanical Design Process. New York; 2003.

Ulrich KT, Eppinger SD. Product design and development [Internet]. Vol. 2. McGraw-Hill; 2011. Available from: http://www.ucalgary.ca/files/schulich/ENEL589_W11_outline.doc

Vidal A. Égologie: Écologie, individualisme et course au bonheur. Grenoble: MONDE ENVERS; 2017. 120 p.

Viswanathan V, Atilola O, Esposito N, Linsey J. A study on the role of physical models in the mitigation of design fixation. Journal of Engineering Design. 2014 Mar;25(1–3):25–43.

Viswanathan V, Atilola O, Goodman J, Linsey J. Prototyping: A key skill for innovation and life-long learning. In: 2014 IEEE Frontiers in Education Conference (FIE) Proceedings. 2014. p. 1–8.

Wall MB, Ulrich KT, Flowers WC. Evaluating prototyping technologies for product design. Research in Engineering Design. 1992 Sep;3(3):163–77.

Dr. Marianna Joy Coulentianos

Dr. Marianna Coulentianos is a lecturer in Responsible Design within SDCA. Marianna leverages principles of socially engaged design, front-end prototyping, and participatory methods of stakeholder engagement for equitable sustainable development. With a background in design for the global South, her current research focuses the role of low techs in post-growth futures.

Designers prototyping in the lab: Introducing an extracurricular activity exploring bacterial colouring in a design educational setting

Monica Louise Gjøderum Hartvigsen, Design School Kolding
Shanice Otersen, Design School Kolding
Karen Marie Hasling, Design School Kolding

Abstract

This paper presents research from an ongoing PhD project on microbial colouring applied to textile design practice and education. In this paper, we study how bacterial colouring can be implemented as an extracurricular activity in a design school setting. By conducting a series of three workshop prototypes combining theory and hands-on experience, we explore how bacteria grow, how a special type of pigment-producing bacteria can be applied to textiles, and how to work with aseptic techniques and handle biological waste. As we were interested in how the students experienced the workshops, we gathered insights during the individual workshops and asked them to fill out an evaluation form.
To understand how theoretical and practical skills have influenced each other in the workshops, we propose a model. The model is used to understand and expand on how workshops can be used to provide and generate knowledge by combining theory and practice from both bacterial dyeing and textile design. We find that the model can be adapted for further workshop activities combining other design disciplines with an overlapping or adjacent discipline like in this study, where it has been biology.

Keywords: Bacterial colouring; Design education; Experiential knowledge

As a response to the environmental impact of the industrial revolution an alternative perspective on production through biofabrication (producing materials from the growth of living organisms or cells) is emerging within the design research field (Myers, 2012). Designers are using biofabrication to be involved in not only *selecting* a material but also *producing* a material and Camere and Karana describe this material design practice as *growing design* (Camere & Karana, 2017).

In addition to design practice, European design schools are beginning to explore and incorporate biodesign as a part of their research and educational focus. In the United Kingdom, the Master's program in Biodesign was launched in 2019 (*Central Saint Martins Launches Masters Course in Biodesign*, 2019). In Finland, the ChemArts Summer School combines material science and design (Kääriäinen et al., 2017; Kääriäinen & Niinimäki, 2019; Kaarianen et al., 2020). In Belgium, the LABORATORIUM at the School of Art Ghent is a place for design students to explore the intersection of design and biotechnology (*LABORATORIUM*, n.d.). In December 2022, the Technical University of Delft opened a biodesign laboratory in conjunction with courses in biodesign (*Opening van het* *hypermoderne Biodesign Lab van de TU Delft*, n.d.). In between design educations and the FabLab maker-movement Fabricademy emerged and provides designers with practical courses on textile, digital fabrication and biology (*Fabricademy Network Worldwide*, n.d.). In addition to the practical development's, studies into the taxonomy (Camere & Karana, 2018; Collet, 2020; Ertürkan et al., 2022) and knowledge on the biomaterials produced by living organisms (Rognoli et al., 2022) have emerged in cohesion with the practical elements.

In this paper we present a study, which has been conducted as part of a PhD project investigating how microbial colours can be applied to textile design practice and education. The research in this paper contributes to the field of biodesign education, by exploring how bacterial colouring can be implemented in design education as an extracurricular activity for students to develop useful skills for biodesign and textile design practice by participating in a series of hands-on bacterial colouring workshops in a design school setting. In the paper, we first introduce our understanding of and use of prototypes in the given research, we then argue for the reasons to develop the structure and content of a series of three workshops followed by a description of the workshops and finally we conclude with our findings and how these can be used for future research.

Prototyping in the context of the workshop

In this paper we discuss prototyping as having a multitude of meanings and modes, from the concrete bacterial pigments and the workshops to the intangible interaction happening among the students present in the workshops.
We align our understanding of prototyping as described by Sanders and Stappers (Sanders & Stappers, 2014; Stappers, 2014). Here prototypes in design research are described to carry out many roles; they evoke a focused discussion in a team; they allow testing of a hypothesis; they confront theories; they confront the world making tangible suggestions and they can change the world via intervening (Sanders & Stappers, 2012).
In figure 1, a visual representation of the different prototypes identified in this study is presented. The representation has been inspired by Redström's continuum between what *a* design is (product) to what designing is (paradigm) (Redstrom 2017), translated here into a continuum from a physical outcome (left) to the framing and design pedagogic and structural considerations (right). Hence, we see the prototypes presented here in different ways as carriers of concrete knowledge relevant for design research, which can be extracted and shared with others.

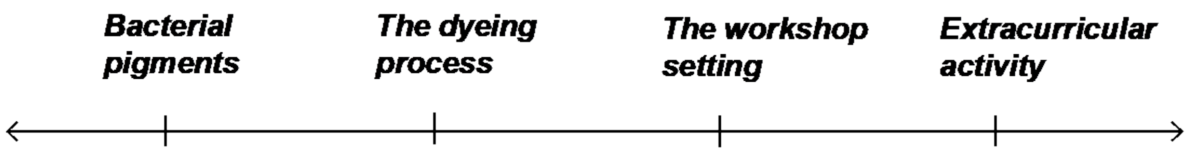


Figure 1: The different modes of prototypes in this research.

Below we provide an overview on the different modes of protypes identified in the study together with a question for each prototype to further expand on:

- The bacterial pigments: A concrete prototype of the tangible material applied in the workshops. How to learn about bacterial pigments in a design school setting?

- The dyeing process: A process prototype covering the bacterial dyeing processes, which is applied in the workshop. The first process prototype is the bacteria growing and producing pigment in a closed container with textiles. The second process prototype is the conventional textile dyeing process, where bacterial pigments produced prior to the workshops are used. How to introduce different dyeing processes with bacterial pigments for textile application?
- The workshop setting: A learning activity prototype proposing a frame for introducing knowledge emphasising a practical hands-on approach to students. How to frame a series of workshop activities that supports students' learning a new topic?
- The extracurricular activity: An organisational activity prototype facilitating knowledge exchange between (facilitators and) students beyond mandatory course work. How to use extracurricular activities to advance investigating specific topics for both researchers and students?

Method: Experiential approach to the workshops

The workshops are a part of a PhD project with an overall research through design approach (Koskinen, 2011), and in this study, design practice and prototypes are used as research means to gain insights. This allows the design researcher to actively engage in real-world problems or "*wicked-problems*" by constructing and exploring complex scenarios (Forlizzi et al., 2009).

Here, we are using a workshop setting involving participants and we find it relevant to briefly touch upon the concept of experiential knowledge. As designers and design researchers, we are actively engaging in the design activity; thus, we are using the dialogue and direct interaction between the students and the facilitated reflection for the individual student as means for us to extract knowledge (Niedderer & Reilly, 2011).

To document the interaction and experience, one of the authors was responsible for taking photos throughout the workshops. We also had a notebook to write down reflections after each conducted workshop. This included what we had observed during the workshops but also what the students had verbally expressed. This type of knowledge extraction is building on Schön's understanding of reflection-on-action (Schön, 1991, 1992), where our experiences are used as data for research findings (Mäkelä & Nimkulrat, 2018). In addition, a written evaluation form was developed beforehand to provide a framing for the feedback from the students' experiences.

Motivation for conducting the workshop series

We wanted to introduce the design students to bacterial colouring for several reasons. The first reason was to develop the workshop to provide the design students with a hands-on exploration of an environmentally friendly textile colouring process and learn about alternative bio-colourants, inspired by material tinkering (Parisi et al., 2017).

The second reason was the importance of having a practical element to the workshop. Since designers are used to have hands-on knowledge combined with theoretical knowledge: *"thinking and knowing are inseparable from making in any craft or designerly practices"* (Nimkulrat, 2012:2), we wanted to have an emphasis on mixing theory and experiential knowledge, while maintaining a focus on the practical elements.

The third reason was to use the workshop setting to teach students about biodesign and spark their curiosity about this growing research field. This provides them with introductory knowledge of laboratory work from a natural science perspective but situated in a design school. We believed that this would equip them with the foundational knowledge to explore this field further throughout their design education.

The fourth, and last, reason for conducting the workshops was to generate empirical knowledge for the PhD project conducted by one of the authors, to explore if or how bacterial colouring could be implemented at the design school. Hence the workshop was created as an extracurricular activity, intended for all interested design students at the school.

Creating the workshops

The series of workshops was created based on the pedagogical framing already present at the Design School Kolding. The school, originating in arts and craft, is building on Schön's approach of making and reflecting (Schön, 1991). Part of the research conducted at the school revolves around developing design skills, methods and tools (Bang, 2009b, 2009a; Hartvigsen & Hasling, 2022; Hasling & Bang, 2015; Møller et al., 2016; Ræbild & Hasling, 2019; Riisberg et al., 2014), which students individually or together can combine and develop further to match their individual interests, processes and design disciplines. Therefore, the workshops were also seen as an opportunity to formalise and test a structure for future learning activities within and beyond the curriculum.

The workshops were created as a series of three individual workshops that were building on each other and conducted within three weeks. In figure 2, the overall frame for the workshops is presented including the focus and content for every workshop. Each workshop started with a presentation introducing the theory behind the practical explorations in the individual workshop.

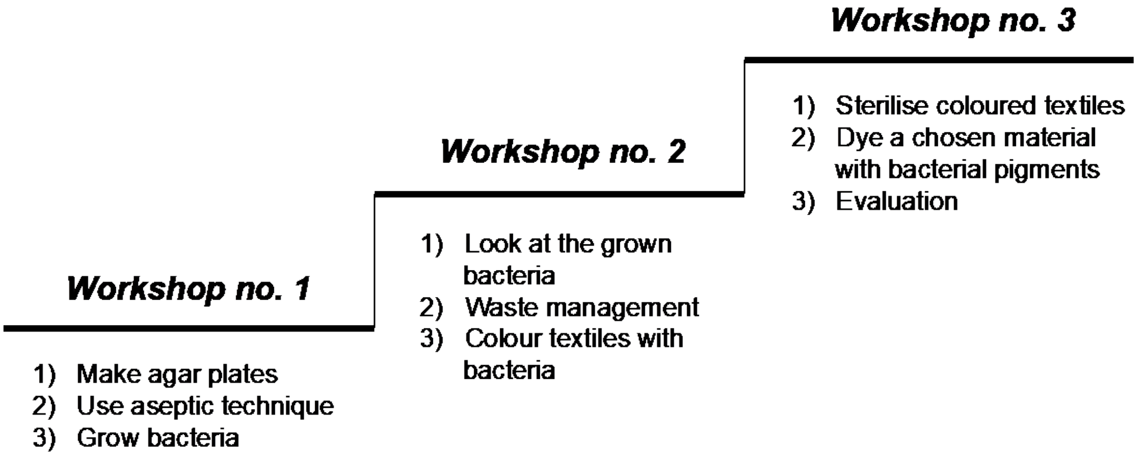


Figure 2: An overview of the content explored in each of the three workshops.

Another practical aspect of dividing the workshops into three parts was to allow time for the bacteria to grow and produce colour, thereby attempting to provide the students a transparent and full process from start to finish of bacterial colouring.

Conducting the workshops

The three workshops were conducted at the Design School Kolding and exclusively offered to the school's students. To attract students to join, all students were invited via email with a poster describing the workshop series. Out of the 350 students, 60 wanted to sign up, which indicates the relevance and interest in the given topic.

However, as the workshop space and resources were limited, we had to select a smaller group of students to conduct the workshops with. Therefore, we chose 14 students in total–seven textile design students, three fashion design students, three industrial design students, and one communication design student–and divided them into two groups.

One group (Group 1) predominantly consisted of students from the same interdisciplinary master's program and year, which, in parallel with the workshop, had a course on material roles in design for sustainability that initially served as a framing and context for the workshop series, while the other group was composed of a mixture of students from different disciplines and years (Group 2).

Workshop no. 1

In the first workshop, the students were introduced to the basics of how to work with microorganisms by showing them how to prepare a nutritious solution for creating agar plates and letting them actively participate in the process.

A crucial step during this phase was to autoclave the solution in a pressure cooker to ensure the absence of unwanted bacteria or microorganisms. This meant that the solution had to sit inside the pressure cooker for approximately 30 min. During this time, we gave the students a presentation about the theoretical part of the workshop in a separate classroom. The presentation entailed introducing them to what bacteria are, how to cultivate them, how to work with them in a sterile manner, and practical input regarding the next steps in the workshops.

After the autoclave process was completed, the students were brought back into the lab, and shown how to pour the liquid medium into petri dishes to create the finished agar plates. This was done by showing them how to do it and ensuring that the most crucial steps were pointed out. Afterwards, the students went up one by one to try out the process under the supervision of the workshop leader. The agar plates must be poured when the solution is still warm and must be set for a couple of hours to solidify. Therefore, the students proceeded to work with premade agar plates in the next steps, see figure 3. They were asked to swab different surfaces for bacteria at the school, transfer them onto agar plates, and label them with their name, date, and the area they had swabbed. The workshop concluded by briefly touching upon what the students could expect from the next workshop and explaining what would happen to the agar plates that they had created.

Figure 3: Workshop no. 1 – (from left to right) Students are preparing agar plates, they are writing on the agar plates and using them swap surfaces to grow microorganisms from the local surroundings.

Workshop no. 2

The second workshop was initiated with an introduction and discussion of waste management in a biolab setting. The students reviewed the results of their previous experiments on swabbing different surfaces and instructed on how to grow bacteria on fabric swatches. We started the workshop by showing the students the results of their previous experiments and had a casual conversation about the results, as well as letting them discuss their results amongst each other, see figure 4 (middle). Furthermore, the students were shown how the agar plates that they had poured in the last workshop turned out and given input on which ones turned out well and were usable and which ones were not, clarifying which mistakes could be avoided in the future.

In the next step, students learned how to dispose of their waste properly when working with living organisms. They were asked to place the previously discussed agar plates in an autoclave bag and close them with tape. The bags were then placed in a pressure cooker and sterilised for 30 min. In the meantime, the students received another theoretical lecture as preparation for the practical part of the workshop as well as background information about dyeing with bacteria. We also showed them fabric samples that were dyed with a bacterial dye as examples of what the fabrics they would work with might look like. As the students returned to the lab, they were shown that it was now safe to dispose of sterilised plates in the residual waste bin.

We prepared several autoclaved bags with undyed textile swatches, each containing different types of textiles such as wool, cotton, and polyester. Furthermore, we brought in previously sterilised liquid growing medium and agar plates that carried streaks of two different pigment-producing bacteria: one that produced a yellow pigment and one that produced a blue/violet pigment. The students could choose one bag of swatches each and choose which bacteria they wanted to use to dye their swatches, see figure 4 (right). It was emphasized that not all bacteria would produce the pigment, as we were working with wild-type bacteria, which cannot always be controlled to produce colour, although applying the same process.

Therefore, students would have to share their final results with each other so that everyone could obtain a dyed sample. The students were then shown how to pour the medium into the textile bags, streak the bacteria from the agar plate, and transfer it into the bags. As in the previous workshop, the students came up individually and carried out the process under the supervision of the workshop instructor. At the end of the workshop, we explained what the students would expect from the next workshop and asked them to bring in material samples that they would like to dye.

Figure 4: Workshop no. 2 – (from left to right) Students are looking at the microorganisms from the local surroundings, they were introduced to cultivate pigment producing bacteria and prepared textiles with pigment producing bacteria in a local sterile environment.

Workshop no. 3

In the final workshop, the students sterilised the fabric samples they had made in workshop no. 2 and learned how to dye them with pre-sterilised bacterial pigment dye. At the start of the workshop, the bacteria-dyed textiles made in Workshop no. 2 were shared, and the students were encouraged to discuss them.

Prior to the workshop, we autoclaved the bags of dyed textile samples, so they were ready for the students to open, wash and dry, see figure 5 (top row). While the samples were drying, the students entered the presentation room for the theoretical part of the workshop. In this lecture, they were introduced to different bacterial pigments, including their molecular structures, to understand why the pigments bind to the fabric. Moreover, the students were introduced to the practical part of the workshop: dyeing with sterilised bacterial pigments.

Back in the lab, we asked the students to find the materials they had brought with them. We then asked them to place the samples in previously prepared jars, containing 40 ml of bacterial pigments, and then filled the jars with water until the samples were fully submerged. The students were then asked to place the jars with their samples in a large pot partially filled with water. After all the jars were placed inside the pot, we explained that the pot would be heated for at least 30 min, so that the hot steam would fix the pigment to the materials. During the time needed to fixate the pigment, the students returned to the presentation room and were asked to fill out an evaluation form for all three workshops.

Afterwards, the students took their samples out of the jars and placed them onto a grid, where they could observe how the colour had been absorbed by the different types of materials, and discuss and compare them in the group, see figure 5 (bottom row). To conclude the workshop series, the students shared their dyed samples from Workshop no. 2 and took home the samples from Workshop no. 3.

Figure 5: Workshop no. 3 – (top row) Students look at the textiles which have been coloured by the pigment producing bacteria. (bottom row) Students use already prepared bacterial pigment to colour various materials.

Findings from the students

To further gather student's insights from the workshop series, after the final workshop they were asked to fill out an evaluation form. While the ongoing discussion and reflection focused more on the individual workshops. We used the evaluation form get the students to reflect on the workshops as a whole. We received twelve evaluation forms, since two of the students were not able to participate in the last workshop.

In the following section we will describe the students' feedback and insights using the prototype hierarchy introduced in figure 1 to guide the insights.

Bacterial pigments

We had planned the workshops around the possibilities of the bacterial pigments. Hence it was difficult to separate the bacterial pigments from the dyeing process. The students had good reflections on the potential of the bacterial pigments.
One student was wondering whether it was possible to manipulate the patterns that the

bacterial pigments created, while another student responded that it was difficult to work with bacteria as a designer, because the outcome is so spontaneous.

The dyeing process

In the evaluation form, the students were asked to describe their thoughts on the designs that came out of the bacterial dyeing process. The majority of students responded that they liked the organic and unique designs given by this kind of dying process and that they liked the imperfections and found the designs to be meaningful and inspiring. *"I feel very inspired, and I think it is still (a) quite unexplored technique for designers, so I'm glad I could try it."*

The workshop setting

As a part of the evaluation, we asked the students to grade the workshop from being boring (grade 1) to being interesting (grade 5). Based on this, the average grade was 4.67, which corresponds with the general impression that students found the workshops to be interesting. In the evaluation form, the students were also asked to describe how they experienced the workshops and here their responses were similarly positive. Many of the students responded that they found the workshops interesting and insightful while others answered that they learned something new and got inspired and that they liked working with a different medium. They furthermore responded that they liked the hands-on approach and the combination of theory and practice. One of the participants stated "*it was really interesting to discover new natural alternatives to chemical dyeing. Also, I really liked the fact that we were both provided with theoretical courses and hands-on practices."*

Since we had structured the activity as a series of three consecutive workshops, we were interested in better understanding, which workshop the students found most interesting and relevant. Two students favoured Workshop 1, six students favoured Workshop 2, four students favoured Workshop 3 and one student favoured all workshops equally or favoured them as a whole.

While many students found Workshop no. 2 more relevant and interesting as they got to work with bacterial dye and "*see the magic happen*", many also stated that they liked the combination of all three workshops. One student said *"I loved all workshops equally since all of them had both theory and practice. Seeing the results is as exciting as doing the agar petri dish."*

In the evaluation form, we also asked the students which parts of the workshops they found to be difficult and which parts they found to be easy. The students overwhelmingly replied that the workshops overall were easy to follow and very understandable. Many answered that they did not find the workshops difficult at all, while several others replied that it was challenging for them to work in a sterile way.

We also asked the students if they would like to change anything about the workshops. Most of the students responded that they would have liked even further theoretical explanation about bacterial dyeing and getting to know more about one of the author's PhD project with bacteria. Several students responded that they would have liked to create a bigger piece of bacterial dyed fabric and to be able to design patterns and products, as well as wanting to receive more tips on how to get started with biodesign on their own. One student responded that it would have been great to receive a leaflet with more detailed information about the workshops.

Extracurricular activity

As we were also interested in understanding the potential of the workshop series as an extracurricular activity with the same or similar topic, in the evaluation form, the students were asked if they could imagine working with biodesign in the future and if they would be interested in taking part in further biodesign workshops for example about mycelium or kombucha. Except for one student, who was not interested in pursuing biodesign, all others replied that they find it an interesting topic that they would like to incorporate in future projects. One student stated: *"I believe that there is a lot to explore in the field and I see great potential on this approach in specific."*

Findings from our experience as workshop facilitators

The following section will focus on our experiences as workshop facilitators using the identified prototype hierarchy to guide the insights.

Bacterial pigments

During the workshops, we saw that the students were good at reflecting on how they could apply bacterial colouring and living materials to their own design discipline. This sparked interesting conversations during the workshops on how the students could proceed if they wanted to continue working with bacterial pigments, thus creating new connections between students with similar interests.

The dyeing process

As already mentioned, the bacterial pigment and the dyeing process are closely connected. The students were mostly interested in the dyeing process using the living bacteria, as it was an approach which the students had not experienced before. Most of the students had a background within textile and fashion and therefore knew about the process of conventional dyeing, which were the other approach to the bacterial dyeing process.

The workshop setting

As facilitators we experienced how the students participated in the workshops. Here we could observe, how students from Group 1 (predominantly students from the same course and year) found it easier to approach the workshop format and content, while students from Group 2 (mixed group of students) had more questions, found it difficult to discuss output and reflect on insights from the workshop with each other during the workshops. Here it can be relevant to mention that the workshops were conducted in English, the language commonly used for the master students, but not for the bachelor students, which might have made some more reluctant to actively engage in conversations.

Extracurricular activity

From the workshops, we were interested in gaining insights on the students' willingness to and motivation for engaging in extracurricular activities building on and advancing concepts and methods introduced as part of the curriculum but also to enable students – and us as researchers – to explore new and emerging topics that might not fit into or have not yet found their way into the curriculum. To discover the balance between what to offer as part of the curriculum, what to offer as extracurricular activities internally in the school and what to propose to and expect from students to take initiative and explore on their own.

Some students asked us, in case they wished to explore the biodesign field further, how to continue on their own, since they felt a barrier towards continuing on their own. It would thus be interesting to follow students as they continue their educational journey, to see if they incorporate biodesign into their practice.

Proposing a model to navigate between prototype hierarchies

Based on the identified hierarchy of prototypes and findings from the practice-based study engaging students, we find it relevant to elaborate on this based on a proposed model used to navigate between prototype hierarchies and that considers the design discipline (or sub-discipline) in dialogue with overlapping or adjacent disciplines (vertical axis) and that promotes input from theory-based knowledge as well as a practice-based skillset (horizontal axis). Visually, the model has been inspired by the shape of neurons and illustrates how knowledge and skills relate to each other, see figure 6. Dependent on the emphasis of the four domains, the shape of the model can be altered.

Here the workshop format has been valuable as a protype to explore and expand on the model to understand the overall framing and mindset needed to facilitate the meeting between different disciplines.

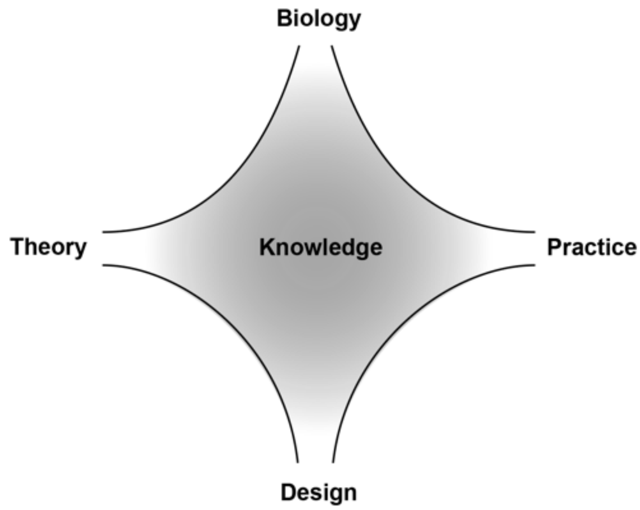


Figure 6: The general model where there is an equal distribution between theory, practice, biology and design.

The model illustrated in figure 7 shows how the different knowledge and skill domains that the students have engaged with during the workshop series connect to create new knowledge. The knowledge and skill contributions are shown as bubbles that are feeding into a pool of shared and common knowledge at the centre of the model.

In this particular workshop series prototype, we wanted to bring together bacterial dyeing and textile design practice and the majority of students participating came from fashion and textile design. As textile design to them is a familiar domain where students come with prior knowledge and practice experience, we experienced that they found it easy to understand and engage in the workshops.

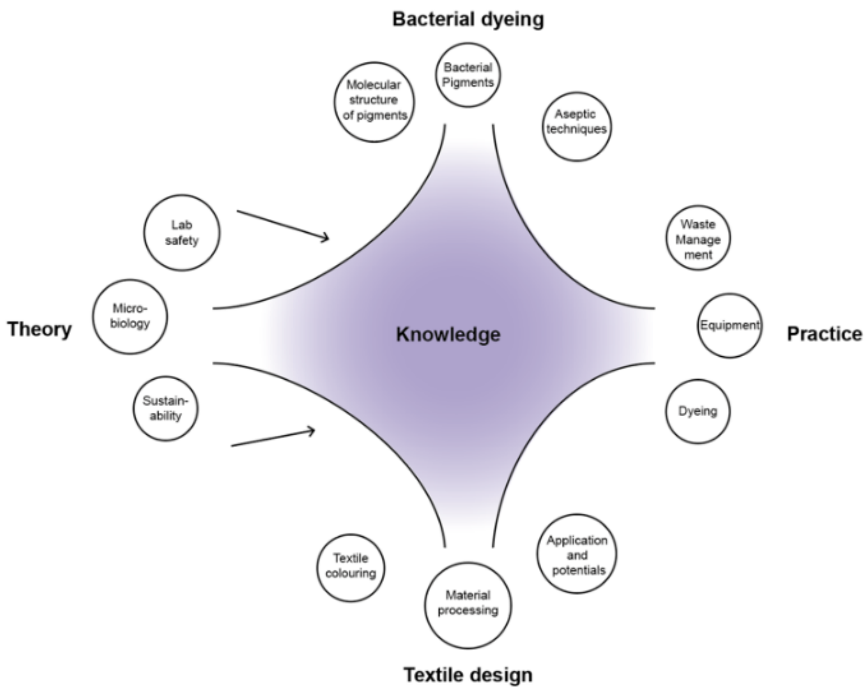


Figure 7: The model used to illustrate relevant aspects of the study - within and between the four domains and how domains push the balance of the overall frame.

The model can also be used to describe and illustrate the focus of workshops and other learning activities, by shifting its centre between the domains, depending on the target group of the workshops e.g., other groups of students or other professional disciplines. In this way it could be adapted to suit more advanced students, who want to know more about the theory and practice behind a topic, as illustrated in figure 8.

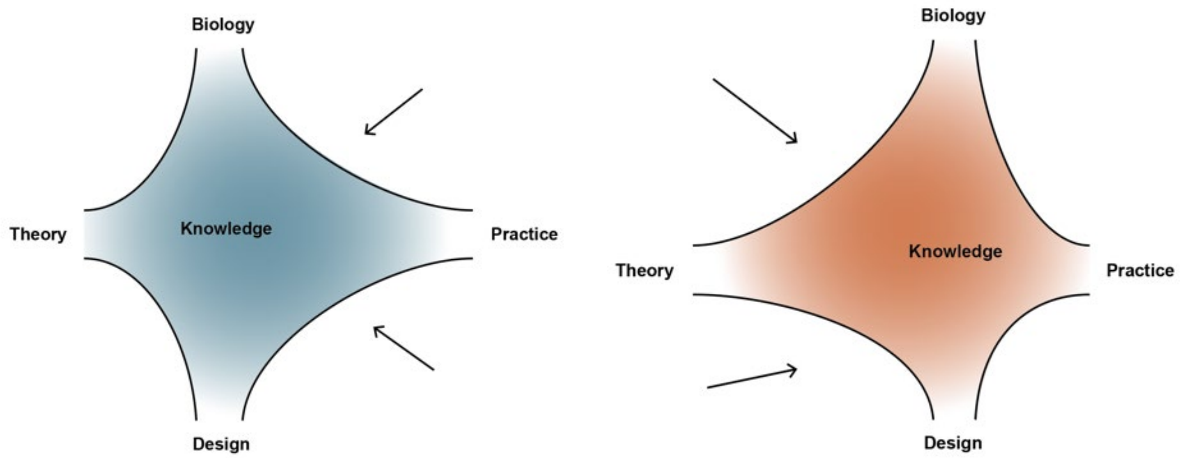


Figure 8: Left: the model where focus has been shifted towards theory and biology and right: the model where focus has been shifted towards design and practice.

Because the model emphasizes the connection of knowledge and skills from different domains and sub-domains, we see that the model can be used for other workshop prototypes that have a focus on bringing together design practice with biological practice as well as possibly a design practice with other intersecting or adjacent practices, see figure 9.

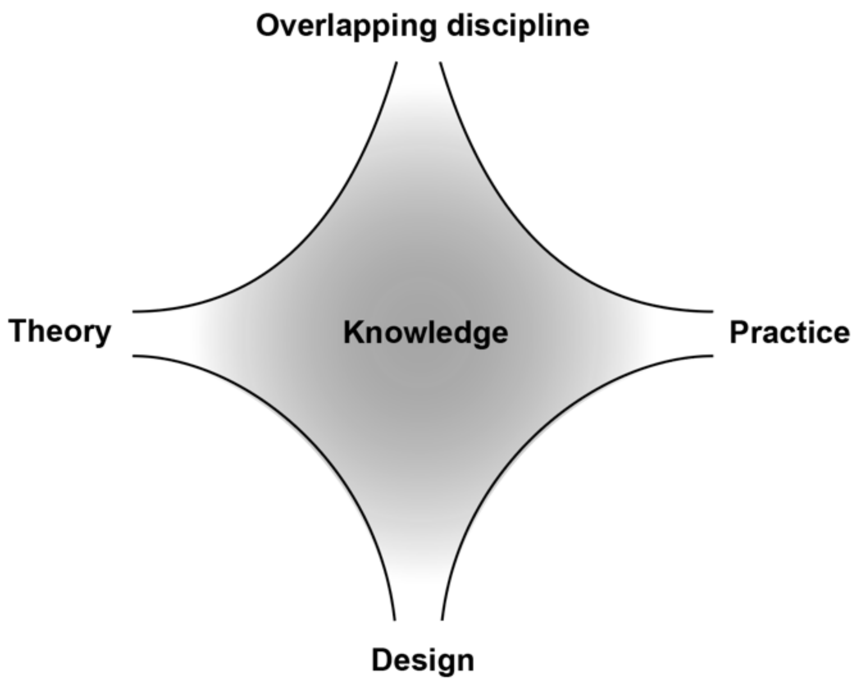


Figure 9: A proposal for a general model where there is an equal distribution between theory, practice, the overlapping discipline and design.

Conclusion

In this study we have investigated how bacterial colouring could be implemented in a design school setting using a workshop format.
We described our prototype hierarchy of the different roles of protypes in this study: *bacterial pigments; the dyeing process; the workshop setting and the extracurricular activity*.
By conducting a series of three hands-on workshops we introduced the students to bacterial colouring combined with textile design practice. In this first workshop we introduced how to grow bacteria, in the second workshop we introduced how to apply pigment producing bacteria to textiles using aseptic techniques and handle waste and in the third workshop we introduced how the bacterial pigment could be applied in a conventional dyeing process.

The students found the bacterial pigment and the dyeing process interesting and had some good reflections over the possibilities of how they could continue exploring the bacterial pigments. Overall, they all found the workshops inspiring, although most of the students favoured the second workshop. They also expressed an interest in joining other extracurricular activities exploring biodesign.

As workshop facilitators we experienced that the students were engaged and enjoyed the mix of theory and hands-on explorations. For understanding how the theory and skills had influenced each other we developed a model which helped us visualise how the knowledge was achieved in this particular series of workshops combining bacterial dyeing with textile design practice. We propose this model can be used for further workshop prototypes combing the design discipline with biology or other overlapping or adjacent disciplines.

Acknowledgements

We are extremely grateful for all the design students at Design School Kolding who wanted to participate in the workshops and provide us with useful insights for this research.
We also want to thank *The Danish Foundation for Entrepreneurship* for supporting us to develop the workshop format and conducting the workshops.

References

Bang, A. L. (2009a). The Designer as Facilitator: Actively Involvement of End-users in the Design Process. Proceedings of the XX ISPIM Conference. The Future of Innovation, The XX ISPIM Conference. http://www.ispim.org/index.php/publications

Bang, A. L. (2009b). Triads as a Means for Dialogue about Emotional Values in Textile Design. Design Connexity: Proceedings of the Eighth European Academy of Design International Conference, 44–49. https://adk.elsevierpure.com/da/publications/triads-as-a-means-for-dialogue-about-emotional-values-in-textile-

Camere, S., & Karana, E. (2017, June 19). Growing materials for product design.

Camere, S., & Karana, E. (2018). Fabricating materials from living organisms: An emerging design practice. Journal of Cleaner Production, 186, 570–584. https://doi.org/10.1016/j.jclepro.2018.03.081

Central Saint Martins launches masters course in biodesign. (2019, May 21). Dezeen. https://www.dezeen.com/2019/05/21/central-saint-martins-biodesign-ma/

Collet, C. (2020). Designing our future bio-materiality. AI & SOCIETY. https://doi.org/10.1007/s00146-020-01013-y

Fabricademy Network Worldwide. (n.d.). Google My Maps. Retrieved 16 April 2023, from https://www.google.com/maps/d/viewer?mid=1AamJT5LF7HULgMKaIp5XKM3gKu0O5MnE

Ertürkan, H., Karana, E., & Mugge, R. (2022). Is this alive? Towards a vocabulary for understanding and communicating living material experiences. DRS Biennial Conference Series. https://dl.designresearchsociety.org/drs-conference-papers/drs2022/researchpapers/304

Forlizzi, J., Zimmerman, J., & Stolterman, E. (2009). From Design Research to Theory: Evidence of a Maturing Field.

Hartvigsen, M. L. (1), & Hasling, K. M. (2). (2022). EXPLORING SENSUOUS QUALITIES OF TEXTILES. DS 117: Proceedings of the 24th International Conference on Engineering and Product Design Education (E&PDE 2022), London South Bank University in London, UK. 8th - 9th September 2022. 24th International Conference on Engineering & Product Design Education (E&PDE 2022). https://doi.org/10.35199/EPDE.2022.25

Hasling, K. M., & Bang, A. L. (2015). How associative material characteristics create textile reflection in design education. Journal of Textile Design Research and Practice, 3(1–2), 27–46. https://doi.org/10.1080/20511787.2015.1210916

Koskinen, I. (2011). Design Research Through Practice: From the Lab, Field, and Showroom. San Francisco: Elsevier Science & Technology. https://doi.org/10.1016/C2010-0-65896-2

Kääriäinen, P., & Niinimäki, K. (2019). Towards Sustainable Textile Materials: Potential pathways and dialogues between disciplines. Nordes, 0(8), Article 8. https://archive.nordes.org/index.php/n13/article/view/476

Kääriäinen, P., Niinimäki, K., & Lindberg, A. (2017). 'CHEMARTSING'—An Experimental, multidisciplinary, collaborative and future oriented pedagogy with wood based biomaterials. REDO: Cumulus REDO Conference. Proceedings, Design School Kolding 30 May-2 June 2017, 252–259. https://research.aalto.fi/en/publications/chemartsing-an-experimental-multidisciplinary-collaborative-and-f

Kääriäinen, P., Tervinen, L., & Vuorinen, T. (2020). The chemarts cookbook.

LABORATORIUM. (n.d.). Retrieved 16 April 2023, from http://laboratorium.bio/

Myers, W. (2012). Bio Design, Nature Science Creativity. Thames & Hudson.

Mäkelä, M., & Nimkulrat, N. (2018). Documentation as a practice-led research tool for reflection on experiential knowledge. FormAkademisk - Forskningstidsskrift for Design Og Designdidaktikk, 11(2), Article 2. https://doi.org/10.7577/formakademisk.1818

Møller, T., Petersen, L. R. M., & Bang, A. L. (2016, November). Tangible Dialogue Tools: Mediating Between Non-verbal Users and Everyday Experts. Nordcode. https://www.ucviden.dk/en/publications/tangible-dialogue-tools-mediating-between-non-verbal-users-and-ev

Niedderer, K., & Reilly, L. (2011). Research Practice in Art and Design: Experiential Knowledge and Organised Inquiry. Journal of Research Practice, 6.

Nimkulrat, N. (2012). Hands-on Intellect: Integrating Craft Practice into Design Research. International Journal of Design, 6, 1–14.

Opening van het hypermoderne Biodesign Lab van de TU Delft. (n.d.). TU Delft. Retrieved 16 April 2023, from https://www.tudelft.nl/2022/io/december/opening-van-het-hypermoderne-biodesign-lab-van-de-tu-delft

Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for *experiential learning and envisioning in product design education. The Design Journal, 20(sup1), S1167–S1184. https://doi.org/10.1080/14606925.2017.1353059*

Redstrom, J. (2017). Making Design Theory. MIT Press. http://ebookcentral.proquest.com/lib/kadk/detail.action?docID=5053269

Riisberg, V., Bang, A., Locher, L., & Moat, A. (2014, April 14). AWARENESS: Tactility and Experience as Transformational Strategy.

Rognoli, V., Petreca, B., Pollini, B., & Saito, C. (2022). Materials biography as a tool for designers' exploration of bio-based and bio-fabricated materials for the sustainable fashion industry. Sustainability: Science, Practice and Policy, 18(1), 749–772. https://doi.org/10.1080/15487733.2022.2124740

Ræbild, U., & Hasling, K. M. (2019). Experiences of the Sustainable Design Cards: Evaluation of applications, potentials and limitations. Fashion Practice, 11(3), 417–442. https://doi.org/10.1080/17569370.2019.1664026

Sanders, E. B.-N., and P. J. Stappers. 2012. Convivial Toolbox. Amsterdam: BIS Publishers. Sleeswijk Visser, F., P. J. Stappers, R. van der Lugt, and E. B.-N Sanders. 2005. "Contextmapping: Experiences from Practice." CoDesign 1 (2): 119– 149.

Sanders, E., & Stappers, P. J. (2014). Probes, toolkits and prototypes: Three approaches to making in codesigning. CoDesign, 10. https://doi.org/10.1080/15710882.2014.888183

Schön, D. A. (1991). The Reflective Practitioner, How Professionals Think in Action. Ashgate.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. Knowledge-Based Systems, 5(1), 3–14. https://doi.org/10.1016/0950-7051(92)90020-G

Stappers, P. (2014). Prototypes as a central vein for knowledge development. In L. Valentine (Ed.), Prototype: Design and craft in the 21st century (pp. 85–97). Bloomsbury Academic.

Monica Louise Gjøderum Hartvigsen

Monica Louise Gjøderum Hartvigsen, BSc Molecular Biology, MA Textile Design, is a PhD Student at Lab for Sustainability and Design at Design School Kolding, Denmark. Her research focuses on microbial colouring for textile application exploring its potential for textile design practice, textile design education and textile design industry.

Shanice Otersen

Shanice Otersen, BA Fashion Design, MA Sustainable Design, is the current project lead for establishing and integrating a biolab into an existing makerspace at the Fablab Spinderihallerne in Vejle, Denmark. She is focused on researching alternative materials in the field of biodesign and was a research assistant to Monica Hartvigsen during this project.

Karen Marie Hasling

Karen Marie Hasling, MSc Design Engineering, PhD is Associate Professor in Learning, Materials and Sustainability at Lab for Sustainability at Design School Kolding, Denmark. Her research focuses on the intersection between materials, design and sustainability looking into engagement and activation of different designer roles and competences from an educational perspective.

Designing Fungal Kinship: From Material to Co-Creator Through Speculative Prototyping

Ana Schacht, Design School Kolding, Denmark
Sofie Kinch, Design School Kolding, Denmark

Abstract

This paper explores speculative prototyping as a way of enabling kinship between humans and non-humans through the pathway of biophilic design. With a theoretical backdrop in post-humanist design, the authors propose that fungi are not only a material for prototyping, but potentially a co-creator of the design process. Through Edward O. Wilson's concept of the 'Biophilia Hypothesis', the paper suggests that the designer's 'fascination' and 'affiliation' should be addressed in order to establish an affective and emotional connectedness to nature. Building upon the design case 'Fungi Kinship', which consists of two workshops and a speculative design prototype the paper offers a renewed technique for prototyping with attention towards multispecies-inclusive design practices. The objective of this paper is to initiate a discussion on how the designer's approach to speculative prototyping can contribute towards creating more sustainable and resilient futures for all living creatures.

Prototyping, Speculative Design, Fungi, Posthumanism, Biophilia Hypothesis

Prototyping has its roots in industrial design practice as a means for designers to convey their concepts or simulate final products (*Tironi et al., 2016; Jönsson, 2017*). Over time, an extensive body of work has examined the role of prototypes, ranging from low-fidelity paper models to highly functional representations of final ideations (*Dalsgaard, 2017*). Prototypes are traditionally considered to be the design-thinking enablers deeply embedded and immersed in design practice and not just tools for evaluating or processing successes or failures of design outcomes (*Lim, Stolterman and Tenenberg, 2008; 7:2*). This points toward the fact that material manifestations in the design process are widely accepted and seen as an essential part of design practice, rather than just a tool for evaluating outcomes. But it also points towards another aspect related to the designer as being in control through his/her form-giving processes.

Prototyping is often associated with materials, techniques, and man-made manufacturing processes such as cardboard, foam and plastic (*Collet, 2017*). This aligns with the way Simon originally referred to design as '*the science of the artificial'* (*Simon, 1969; Cross, 2001*).

In the framing of the existential threat of climate change and the ongoing extinction of other species, the era of post humanist design suggests that the human perspective should no longer be privileged (*Haraway, 2003; Wakkary, 2021*), meaning that it is time for humans to share centre stage with other non-humans actors (*Wakkary, 2021*). This emerging field aims to create new appreciations for other organisms with whom we share our planet and promote a more ecological, porous, and relational understanding of co-habiting for a sustainable future (*Liu et al., 2018; Bellacasa, 2012 and Haraway, 2003)*. As a result, a new form of prototyping, referred to as 'natural prototyping' (*Fraser and Baxter, 2015*) is gaining attention as a way to embody these values.

Researchers and practitioners have proposed numerous prototyping techniques over the years to explore different pathways for expanding the notion and application of prototypes into various research fields. Following the work of Fraser and Baxter, the link between conventional and biological prototyping is philosophically aligned with the concept of Biophilia (*Wilson, 1984; Fraser and Baxter, 2015*), whereas natural prototyping offers a way to promote a more sustainable practice by including non-human perspectives in the design process. In the following, we will unfold the use of prototypes from a speculative design perspective (*Dunne, Raby, 1999; Auger, 2013; Wakkary et al., 2015; Wakkary, 2021*) to introduce the 'Biophilia Hypothesis' (*Wilson, 1984*) as an alternative way of framing the posthuman speculative prototype towards a viable method for creating kinship between humans and non-human species.

Speculative Design Prototypes

In speculative design, prototyping fulfils different purposes and was originally introduced as a means for provoking inspirational responses from users (*Gaver, Dunne and Pacenti, 1999*). Dunne and Raby refer to prototypes as 'para-functionalities', where the speculative design artefact is intentionally crafted to encourage reflections on how technological devices shape (and constrain) people's everyday lives, behaviours and actions in the world (*Dunne, Raby, 1999*). In line with this, the speculative design studio Auger-Loizeau has created speculative design prototypes that emphasize the generation of tensions that conflict with engaged systems in our familiar everyday ecologies (*Auger, 2013*). The purpose is to carefully manage the 'uncanniness' of the design artefact in order to provoke the viewers to interact with the relevant issue(s) (*ibid*). Similarly, Wakkary proposes the use of 'counterfactual artifacts' as a way of creating 'world reasoning', not by the embodiment of the prototypes itself, but as the encounter with, or experience of the artefacts by the interactors, and provoking what might be considered possible or not (*Wakkary et al., 2015*).

By proposing living organisms as the main materiality of the prototype, the focus shifts towards new dimensions and different processes that the designer needs to consider when working along with other species in the framing of speculative design. In the following, we propose using the Biophilia Hypothesis to frame the posthuman speculative prototype as a viable method of creating kinship between humans and non-humans, which is the focus of this paper.

Speculative prototyping with non-humans through the Biophilia Hypothesis

Popularized by Edward O. Wilson in 1984, the Biophilia Hypothesis is understood as the innate drive of humans to seek connections with nature and other species. He defines Biophilia as *the urge to affiliate with other forms of life* (*Kellert & Wilson 1993: 416*). Wilson identifies two conditions for Biophilia to emerge. The first condition, 'fascination', can be defined as the *involuntary attention triggered by Nature* (*Berto, 2005: 11).* In other words, a passive or unintentional focus towards the natural world. The second quality, called 'affiliation', is described as *a willingness to desire a relationship with another non-human creature* (*Barbiero, 2021: 12*). The modern world has distanced humans from nature more than ever in our history, so it is imperative to find new ways of stimulating Biophilia even when nature is not physically reachable. Biophilic design has emerged as the creation of artefacts, services or architectonic spaces that facilitate the qualities of affection and affiliation, necessary to reinforce the vital connectedness with nature.

The paper is structured as follows: the introduction establishes a theoretical backdrop necessary to comprehend the potentials of prototyping within speculative and biophilic design by suggesting the Biophilia Hypothesis in response to posthumanism. We then review previous works regarding the use of fungi as a material and alternately propose a consideration of fungi as a collaborator. We present the design case 'Fungi Kinship' to exemplify and analyze the design of a speculative prototype that enabled a closer relationship between humans and fungi and the interactions it triggered. The paper concludes with a discussion of how prototypes can open up new tangible and as yet unimagined opportunities for more-than-human worlds.

Designing with fungi

The fungi kingdom is one of the most unappreciated, undervalued and unexplored organisms on earth, and despite its vital role in our ecosystems, it is often associated with death and decay (*Stamets, 2005*). As the need for more sustainable future living practices has expanded, so has the intersection between fungi and design. In the relatively new field of Bio Design, the interest in human interaction with fungi refers both to the materiality (*Collet, 2017; Parisi and Rognoli, 2017*) and to the designer's interaction with it (*Parisi, 2017*).

Mycelium, the root-like structure of fungi, can be a suitable alternative to a variety of unsustainable materials used in our everyday life (*Collet, 2017; Parisi, 2017*). In commercial contexts, fungi has been explored within fashion as a leather replacement. Biotechnology companies like Phillip Ross' MycoWorks (*www.mycoworks.com*) or Bolt Threads (*www.boltthreads.com*) have achieved to develop and implement this innovative and sustainable material in the fashion industry. Another approach is seen within the construction and transportation industry, where fungi-based packaging has been developed by the company Ecovative as an alternative to highly polluting packaging materials such as Styrofoam or plastic (www.ecovative.com). Most of these new fungal solutions use the organism as a consumable material (*See Fig. 1*). Once the growing stage is finished, the materials go through a heating process that kills the fungi to stop their development and become a stable material.

*Figure 1. From left to right: Bolt Thread's leather-like Mylo® (Bolt Threads, 2022). MycoWorks collaboration with Hermès made with Fine Mycelium®. (*Coppi Barbieri, 2021*). Ecovative's Mushroom® Packaging. (Ecovative, 2020)*

Fungi as a collaboration-driven design

Designing with living organisms can drastically change the traditional process of designing with a non-living system (*Collet, 2017*). The prototype is generated by the designer as well as the living organism, changing the designer's role from the sole creator of the artefact to becoming a cultivator and enabler of the living organism's own natural processes. In response to the new roles and strategies bio designers should adopt when working with living systems, textile and bio designer Carole Collet developed a framework defined by three pathways: 'Nature as a Model', 'Nature as a Co-worker' and Nature as a Hackable System' (*Collet, 2017*). This paper highlights the second pathway, 'Nature as a Co-Worker', to guide the incorporation of living fungi into speculative prototypes, which is described as:

Co-working with living organisms allows us to incorporate active and dynamic qualities to matter which is not rendered 'victim' of a shape-forming activity, but rather becomes the enabler of the morphogenetic process

(*Collet, 2017:36*). This approach allows for an exploration of the possibility of achieving a sentiment of care and interest for a multispecies world or, as the anthropologist Donna Haraway phrases it, a way of 'making kin' with another being (*Haraway, 2016*). The aim of the design case presented in this paper is, therefore, to examine the potential fungi-human relationship and reconceptualize fungi from something hidden, inanimate and feared, into sentient beings that are both aesthetically pleasing and joyful.

Case study: '*Fungal Kinship'*

The project was developed as part of the first author's MA studies in Speculative Design at Design School Kolding (DK). The research question of the project was: *'How do we tackle the general rejection and lack of knowledge about fungi in order to create a biophilic kinship towards these organisms?'*

The methodological approach was based on a series of design experiments in the form of participative workshop sessions, which led to the design of a speculative design prototype (*See Fig. 2*). The process was continuously inspired by theory readings, material studies, fungi farming, design interventions and user evaluations.

The speculative prototype intended to present a future scenario where humans would be capable of sustaining a relationship with fungi similar to our everyday encounters with domesticated species such as house plants *(Rolighed et al., 2022)* or pets (*Westerlaken and Gualeni, 2016)*. The main premise was that this type of daily engagement with an uncommon species such as fungi could open new possibilities of relating and understanding (*Haraway, 2008*).

Figure 2: Speculative prototype developed for the design case "Fungal Kinship". The device encourages the exploratory use of acoustic interaction, which is interpreted into light and heat, thus affecting the fungi's living conditions.

Two fungi exploration workshops

The workshops were designed to identify the negative connotations associated with fungi and attempt to generate a change in the current behaviour, hence engendering an enriched understanding and relatedness with fungi – in other words, a 'biophilic relationship' (*Wilson, 1984*). To overcome the initial barriers, the first workshop took place in nature, the second one in a laboratory. The inquiries of the two workshops took place over a period of two weeks with a group of approximately 15 people aged 20-30.

The first workshop was scheduled for two hours and took place in the fungi's natural habitat: the forest. The activity was divided into three tasks. Firstly, the participants were asked to complete the sentence: 'When I hear the word 'fungi' I think of...' Next, the participants were encouraged to look for mushrooms and give them a name. Finally, all participants presented their favourite mushroom in plenum and shared their experience.

A main insight identified in this workshop was the capacity of the activity to create an emotional connection with fungi. The most common words written by the participants in the first activity were ‘death’, ‘infection’ and ‘decay’. Some of the participants were even reluctant to touch the mushrooms. After the exercises, the participants stated how pleasantly surprised they were and how their perception of fungi shifted. Most of the names given to the mushrooms recalled pet names, such as ‘Larry’, ‘Lil’ Squishy’, and ‘Mushroomina’, and when they had to share their favourite one, words such as ‘cute’ and ‘amazing’ were often used to describe them (*See Fig. 3*).

Figure 3: One of the participants of the Fungi Exploration Workshop showing her favourite mushroom named “Larry” to the group and sharing her overall experience from the design experiment.

The second workshop (*See Fig. 4)* was intended to push the experience further by shifting the encounter with fungi from its natural environment to a laboratory. The participants were asked to pick different types of substrates for the fungi to digest, such as straw, sawdust, cardboard, banana peels, cigarette butts, fabric scraps, threads and paper. Next, the fungi mycelium was mixed in. The fungi-based materials were then stored to grow under the proper temperature and light conditions. The workshop concluded with each participant sharing their process and their experience. The beauty of the fungi was highly appreciated as an incentive to generate interest in fungi. The workshop permitted the participants to be in close proximity to this organism in a way they had never experienced before, allowing them to undergo a unique sensorial experience. Some of the same users who experienced disgust and fear in the first workshop were in contrast attracted to the smell, the texture of the mycelium and the overall beauty of the fungi.

Figure 4: Participants experimenting with mycelium fabrication in a lab setting.

Design Overview

Based on the insights acquired at the workshops, a speculative prototype was designed to enable a communication system between humans and fungi. In order to conceptualize the prototype, the Shannon-Weaver Model of Communications (*Shannon et al., 1948*) was used to diagram the necessary elements for establishing a communication system between humans and fungi, as shown in Figure 5.

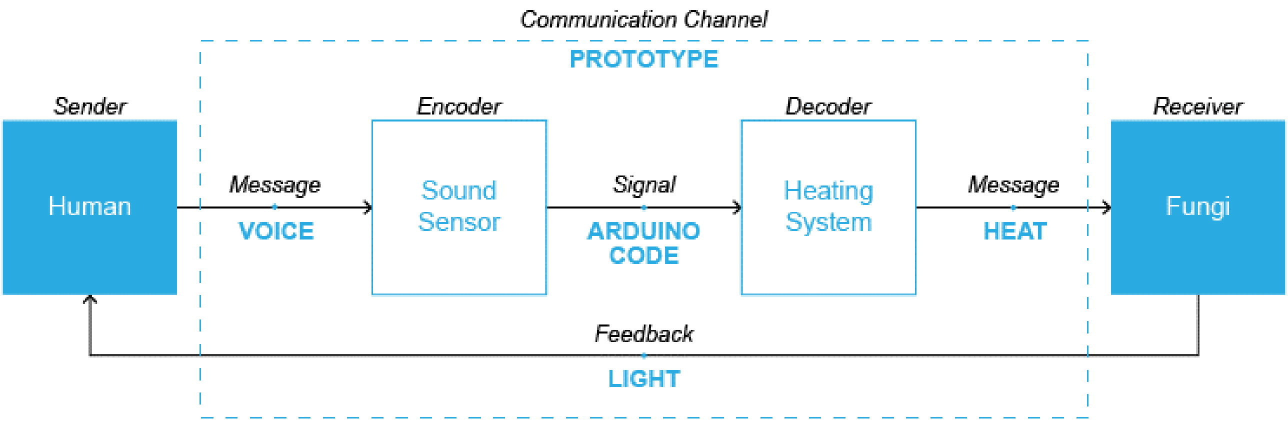


Figure 5: Schematic diagram of the human-fungi communication system enabled by the prototype, adapted from Shannon (Shannon et al., 1948).

Through sonic input, the human user was able to affect the temperature of the incubator (thus influencing the growing conditions of the fungi). A low, subtle voice volume would nurture the fungi to keep growing and eventually produce mushrooms while yelling and shouting would trigger high temperatures causing the demise of the organism. The coloured light feedback visualized how the sonic input would affect the fungi (*see Fig. 6*).

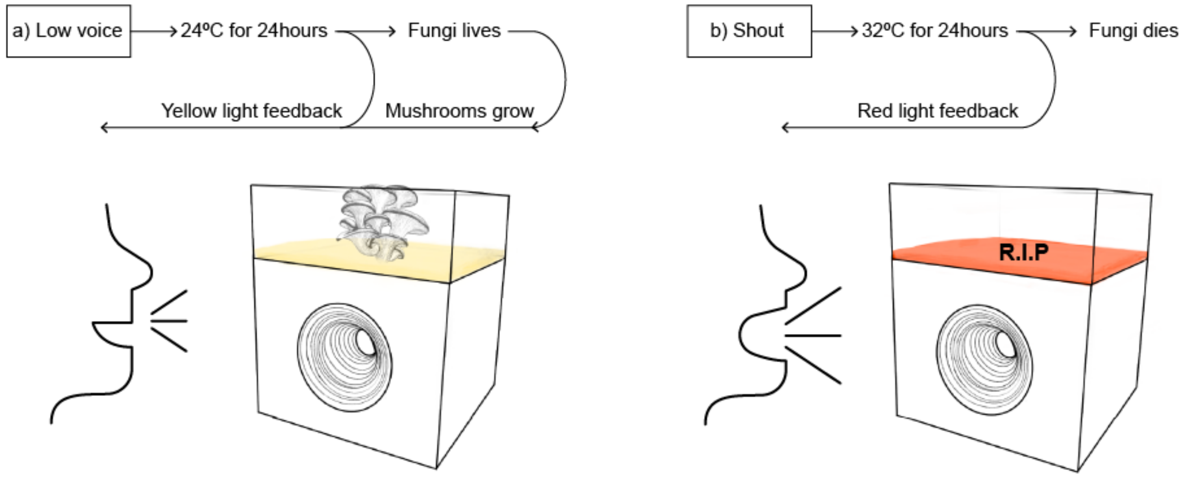


Figure 6: Visualization of how the two settings of the prototype (a) "low voice" and (b) "shout" configured the communication system between humans and fungi.

Materials and methods

The materials and process for developing the elements of the prototype are described below:

Incubator:

Made of 4mm transparent acrylic, the incubator needed to create a sterile environment for the proper growth of fungi. It was also necessary to have modern and clean aesthetics for the appeal of the human users. The pieces were generated using a laser cutter. The edges were sealed with transparent tape for reinforcement and to prevent contamination. Once the mushrooms grew with the incubator sealed, the lid was removed to captivate the senses of vision and smell, engaging the user to experience fungi within a controlled environment.

Figure 7: Incubator

Wooden Intercom:

Pine plywood was chosen due to its clean and warm aesthetics. Designed to resemble a phonograph or a speaker, a concave shape was carved with a CNC router in one of the walls of the box, intending to nudge the users to engage through an acoustic interaction with the prototype. Both the materiality and shape of the intercom invited the users to closely position themselves lower than the fungi in the incubator, challenging new and unconventional interactions.

Figure 8: Wooden Intercom

Fungi:

Based on the speed and resilience to grow under varied conditions, the chosen fungi strain was *Pleurotus Ostreatus,* better known as Oyster Mushroom. A mix of rye and straw was used as the substrate for the fungi to grow in. The mix was sterilized and mixed with mycelium spawn before being placed in the incubator. Slowly taking over the substrate by covering it in white threads, the mycelium created intricate patterns that were visible through the acrylic incubator. After about 10 weeks under the proper conditions, the substrate became completely colonized with mycelium, and ultimately fruited mushrooms that grew over the incubator.

Figure 9: Fungi growing inside the prototype's incubator.

Sound Sensor:

Coloured light feedback in yellow and red visualized how the sonic input would affect the fungi. The light pulsations were coordinated with the voice input, allowing the interaction to demonstrate that the fungi were ‘listening’. The circuit was programmed using Arduino. The components used were an Arduino board, LED 5V strip with RGB programmable colours, a sound sensor, a heating wire and a relay. The circuit was wired and welded into a breadboard and placed inside the wooden box. The sound sensor was placed behind the concave shape where it could best capture the sounds.

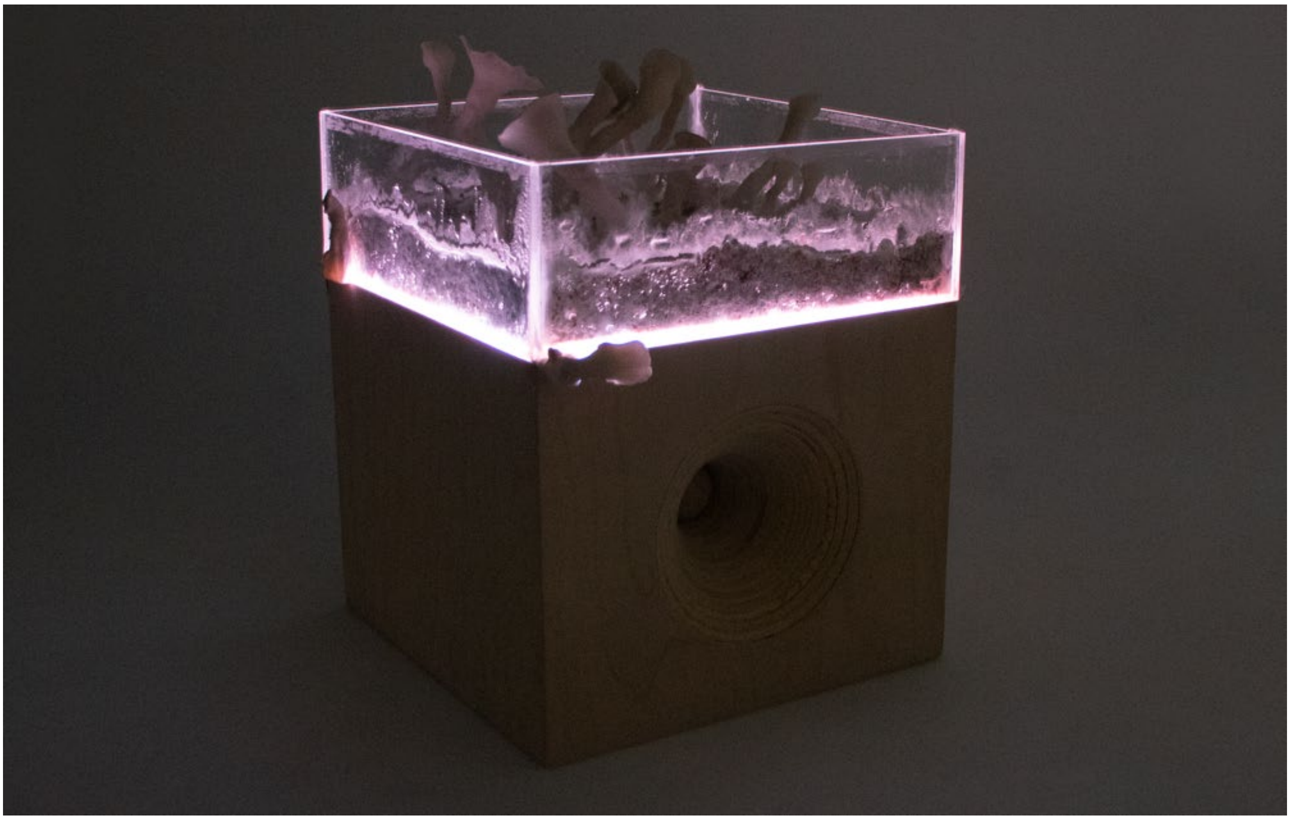


Figure 10: Light feedback reacting to sound sensor.

Heating System:

Temperature is a key factor in the growth of fungi, affecting it in a positive or negative way. The controlled temperature was generated by using a heating wire taken from an upcycled electrical blanket. The sound sensor was programmed to react within a range. The ‘safe’ range was programmed to activate a sustained 23ºC for 24 hours and an output a yellow light feedback. If the volume of the voice that the sensor captured was above the defined range, the light would turn into a continuous red and the heating would blast to maximum potency (32ºC) for 24 hours, endangering the stability of the fungi.

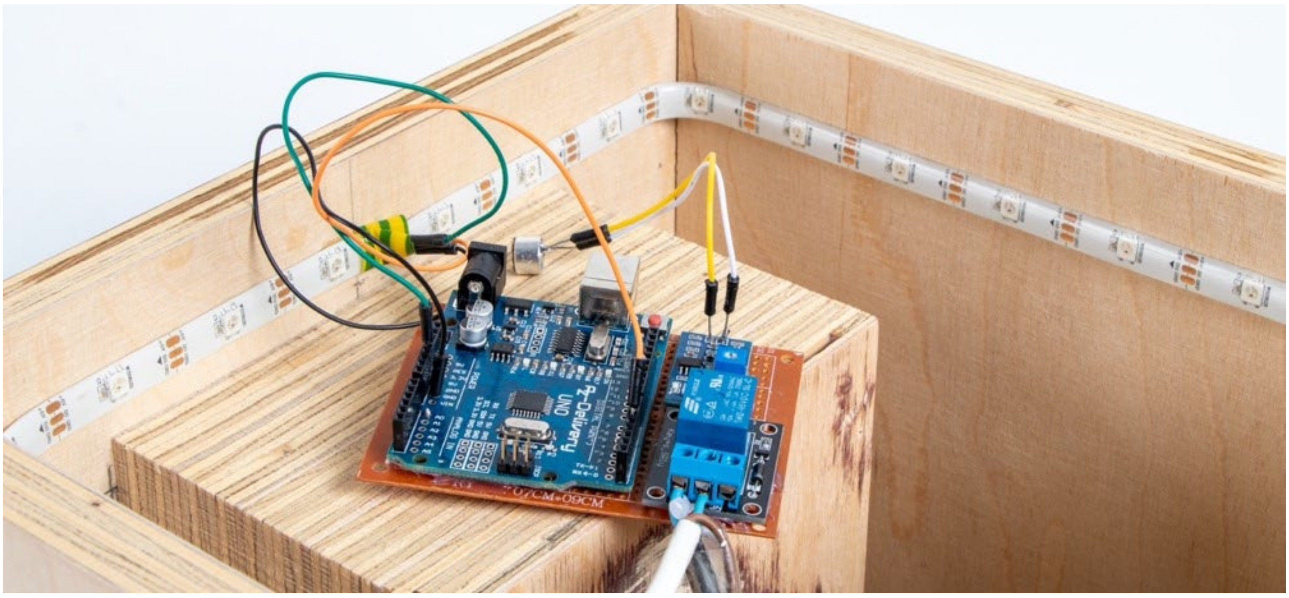


Figure 11: Heating system using Arduino, a heating wire and LED lights.

Evaluating the prototype

The prototype was tested in a lab environment on a group of 6 students, aged 22-28 (*Koskinen et al., 2013*). They were all asked to take a seat in front of the artefact and were given brief instructions on how the prototype worked. Then they were asked to interact with the device, in whatever way they felt like. The session lasted between 12 and 25 minutes during which the designers observed the users´ verbal and nonverbal reactions and collected insights. After the individual sessions, the users were asked to write about their experience and later share it in an open-ended discussion during the evaluation. The intended biophilia was expected to be generated by the primal interaction of verbal communication. We expected that this input would allow users to feel more confident about establishing a relationship with the non-human organism. The verbal communication practices took many forms, as we observed the users whispering, yelling, singing, laughing and telling secrets. Further, we realized that these communication practices were much more than just verbal, as we observed how the users also communicated with the fungi in non-verbal ways, such as touching, caressing, smelling and even kissing. Both non-verbal and verbal communication allowed the users to have novel experiences with fungi, thus enabling the 'affection' and 'affiliation' necessary for biophilia.

In terms of shape and aesthetics, the final outcome of the prototype ultimately depended on the fungi. The designer experienced a new way of reaching the final stage of the prototyping process by embracing the unexpected and relying on trust in the fungi to do their own thing. Clear evidence of this situation occur while the fungi started fruiting mushrooms (*see Fig. 12*). One of the mushrooms managed to grow outside of the incubator box originally intended by the designer to contain the fungi, enabling a whole new interaction with the users, who were remarkably attracted and intrigued by this particular mushroom that 'managed to escape'. This situation taught the designer about adapting to change and made clear how pointless it was to create anticipated expectations on the design. The patience, trust and humility the designer experienced in her interaction with the fungi is evidence of the holistic scope of posthumanism. It not only impacts the end users of the design but is also present throughout the whole process, reshaping the way designers relate to other non-human collaborators.

Figure 12: One of the participants during the testing session, laughing and touching the 'escaping' mushroom that managed to grow outside of the designated space of the prototype.

Prototyping with living organisms: the designer's perspective

Speculative prototyping is an emerging practice that involves creating prototypes that challenge current assumptions and norms (*Gaver, Dunne and Pacenti, 1999*). It is often used to explore the potentials of new technologies and to imagine future scenarios. When applied to biophilic design, this paper suggests that speculative prototyping can be a powerful tool for enabling a relationship of kinship between humans and non-humans.

At the heart of this approach is the 'Biophilia Hypothesis' (*Wilson, 1984*), which suggests that humans have an innate tendency to seek connections with nature and other forms of life. By designing with this in mind, designers can create products and spaces that foster a sense of fascination and affiliation with the natural world. In the project, regarding fungi as living collaborators challenged the design process and the outcome of the prototype. The morphogenesis of the final stage of the prototype relied almost entirely on the fungi itself, whereas the prototype merely served as an enabler of the growing conditions for them to thrive.

From the designer's perspective, becoming a co-creator with the fungi was perceived as a humbling experience, emphasizing a new kind of relationship with this non-human species. Prototyping along with living fungi required not only a domain in the use of design tools and prototyping, but also knowledge about mycology – the study of fungi – in order to comprehend their life cycles, provide a sterile environment, identify optimal substrates and create proper conditions in terms of humidity, temperature, required CO2 exchange and much more. Sometimes it felt more like being a biologist than a designer, proving how these two fields can be intertwined resulting in a more holistic, multi-species and post-humanistic approach to design.

The focus on living fungi sparks a debate, as fungi are often overlooked and undervalued in our society. By using fungi as a starting point, designers can help to raise awareness of their importance and promote a greater understanding of the role they play in ecosystems. Through the creation of two workshops and a speculative prototype, we explored the dilemmas that arise when humans and non-human species come into unexpected contact and seek to develop ways to promote a more harmonious relationship.

It is important to mention that in order to rigorously prove the effectiveness of the prototype of enabling biophilia, much longer and exhaustive testing is required. Temporality is an important factor when prototyping with living organisms, due to their own natural growth pace and the effect on the artefact. On that note, we argue that the use of speculative prototyping in comparison to a more traditional prototype can allow itself some freedoms, as its main purpose is to allow the generation of awareness and discussion about future interactions, rather than a more practical or technical objective like performance, usability or function testing. This alternative purpose can be accomplished by configuring a fictional situation that is convincing enough to allow the user to engage with the prototype and experience the intended scenario without the restrictions of the present reality. As stated by Dunne and Raby, the design speculations must not be treated *as narratives or coherent 'worlds' but as thought experiments – constructions, crafted from ideas expressed through design – that help us think about difficult issues...They allow us to step outside reality for a moment to try something out. This freedom is very important* (*Dunne, Raby, 2013: 20*). In other words, the creation of these prototypes and design experiments with no specific purpose or clear outcome can effectively stage the scenarios for imagining more sustainable futures that could bridge the gap between humans and non-humans (*Binder et al., 2015; Jönsson et al., 2014; Tironi et al., 2020*).

The temporality of the process depended on the natural timeframes of fungi, which required patience from the designer to let nature follow its course. As the old Patagonian saying goes, 'whoever rushes in Nature wastes their time'. This process could not be rushed, lest the prototype would be contaminated, and the experiment would have to start from scratch. Respecting the pace of other living species made us reflect on how we as humans often fail to implement designs successfully by turning a blind eye to nature's own temporalities, making them less resilient or transcendental.

The aim of this approach is to enable users to imagine multispecies-inclusive realities and to rethink more sustainable design practices. By encouraging people to think beyond the needs of humans alone, designers can promote a more holistic and interconnected approach to design that considers the needs of all living beings. This can help to create a more sustainable and resilient future for all.

Conclusion

This paper proposes the use of living fungi in speculative prototypes as an enabler of 'making kin' from humans towards the unappreciated fungi kingdom, through the design of biophilic qualities. By analyzing the design case we can argue that speculative prototypes can re-examine the relationship between humans and fungi (even when there is no physical proximity to nature) by facilitating a fictional and less confined scenario that allows the users to raise awareness, engage in discussions about posthumanism, and generate a sentiment of kinship towards fungi. The fact that most of the fungi's life cycle happens underground, invisible to the human eye, makes the speculative prototype even more relevant through its capacity to make something visible and tangible through the materialization of speculation. This is evidenced in the testimony of one user: *I would never have gotten that close to a mushroom in a forest, especially if I don't know if it is safe, but in this clean and nice setting where I am forced to come face to face with the mushroom, I feel I can safely touch, smell and admire the fungi.*

As a final discussion, this paper argues that having another organism as a collaborator when prototyping with living fungi can reshape the designer's own practice. Different processes transformed the role of the designer, who had to consider slower temporalities, cultivation and husbandry practices and deal with unknown final morphogenesis. All these factors made the designer experience trust, patience, humility and respect, evidencing the potential of speculative prototyping with living organisms as an effective method to propose more inclusive and sustainable futures.

References

Auger, J. (2013). Speculative Design: Crafting the Speculation. Digital Creativity, 24, 1 11-35.

Barbiero, G. (2021). Affective Ecology as Development of Biophilia Hypothesis. Visions for Sustainability, 16, 5575, 1-35 http://dx.doi.org/10.13135/2384-8677/5575

Bellacasa, M. (2012). Nothing Comes Without Its World: Thinking with Care, The Sociological Review, 60(2), pp. 197–216. doi: 10.1111/j.1467-954X.2012.02070.x.

Berto, R. (2005). Exposure to Restorative Environments Helps Restore Attentional Capacity. Journal of Environmental Psychology, 25, 249-259

Binder, T., Brandt, E., Ehn, P., Halse, H. (2015). Democratic Design Experiments: Between Parliament and Laboratory. CoDesign, 11:3-4, 152-165

Bolt Threads, USA, accessed 25 January 2023, < https://boltthreads.com/>

Bolt Threads (2022), digital image*, accessed 25 April 2023,* <https://boltthreads.com/technology/mylo/>.

Collet, C. (2017). 'Grow-made' Textiles. Design & Living Systems Lab, Central Saint Martins, University of the Arts, London, UK.

Coppi Barbieri (2021) MycoWorks, digital image, accessed 25 April 2023, <https://www.mycoworks.com/introducing-sylvania-by-hermes>.

Cross, N (2001) Designerly Ways of Knowing: Design Discipline Versus Design Science

Dalsgaard, P. (2017). Instruments of Inquiry: Understanding the Nature and Role of Design Tools. International Journal of Design, 11(1), 21-33.

Dunne, A. (1999). Hertzian Tales: Electronic Products, Aesthetic Experience, and Critical Design. MIT Press, Cambridge, MA

Dunne, A., Raby, F. (2013). Speculative Everything: Design, Fiction, and Social Dreaming. The MIT Press

Ecovative, USA, accessed 25 January 2023, <https://www.ecovative.com/>

Ecovative (2021), digital image*, accessed 25 April 2023, <https://www.ecovative.com/pages/packaging>*

Bruce, F., & Baxter, S. (2015). From Natures' Prototypes to Natural Prototyping. In G. Bingham, D. Southee, J. McCardle, A. Kovacevic, E. Bohemia, & B. Parkinson (Eds.), Great Expectations: Design Teaching, Research & Enterprise: Proceedings of the 17th International Conference on Engineering and Product Design Education (pp. 272-277). The Design Society & The Institute of Engineering Designers.

Gaver, W., Dunne, A., Pacenti, E. (1999). Design: Cultural Probes*. Interactions. 6. 21-29. 10.1145/291224.291235.*

Haraway, D. (2003). The Companion Species Manifesto: Dogs, People, and Significant Otherness. Vol. 1, pp. 3-17. Chicago.

Haraway, D. (2008). When Species Meet. Minneapolis: University of Minnesota Press.

Haraway, D. (2016). Staying with the Trouble: Making Kin in the Chthulucene. Duke University Press Books.

Jönsson, L., Lenskjold, T. (2017). Speculative Prototypes and Alien Ethnographies: Experimenting with Relations beyond the Human. Disena.

Kellert, S., Wilson, EO. (1993) The Biophilia Hypothesis*, Island Press, Washington.*

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., Wensveen, S. (2013) Design Research Through Practice: From the Lab, Field, and Showroom in IEEE Transactions on Professional Communication, vol. 56, no. 3, pp. 262-263, doi: 10.1109/ TPC.2013.2274109.

Lim Y., Stolterman E., Tenenberg J. (2008) The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas. *ACM Trans. Comput.-Hum. Interact. 15, 2, Article 7. https://doi.org/10.1145/1375761.1375762*

Liu, J., Byrne, D., Devendorf, L. (2018). Design for Collaborative Survival: An Inquiry into Human-Fungi Relationships. In Proceedings of the CHI Conference on Human Factors in Computing Systems, ACM, New York, (CHI18), 1-13

MycoWorks, Philip Ross, USA, accessed 25 January 2023, <https://www.mycoworks.com/>

Rolighed, M., Aagaard, E. M., Jensen, M., Frankjaer, R., Koefoed Hansen, L. (2022). Plant Radio: Tuning in to Plants by Combining Posthumanism and Design. In Designing Interactive Systems Conference (DIS ,22). Association for Computing Machinery, New York, NY, USA, 666–676. https://doi. Org/10.1145/3532106.3533517

C. E. Shannon (1948) A Mathematical Theory of Communication, *The Bell System Technical*

Journal, vol. 27, no. 3, pp. 379-423. doi: 10.1002/j.1538-7305.1948.tb01338.x.

Simon, H (1969) Science of the Artificial. *Cambridge MA: MIT press*

Stamets, P. (2005). Mycelium Running: How Mushrooms Can Help Save the World. Berkeley, Calif: Ten Speed Press.

Tironi M., Hermansen P., Neira J. (2016). The Prototype as a Cosmopolitical Place: Ethnographic Design Practice and Research at the National Zoo in Santiago, Chile. Proceedings of DRS 2016, Design Research Society 50th Anniversary Conference. Brighton, UK, 27–30 June 2016.

Tironi, M., Hermansen, P. (2020). Prototyping Coexistence: Design for Interspecies Futures. ARQ Santiago, Chile. 38-47. 10.4067/S0717-69962020000300038.

Tsing, A. (2012). Unruly Edges: Mushrooms as Companion Species for Donna Haraway. University of California, Santa Cruz, USA

Wakkary, R., Odom, W., Hauser, S., Hertz, G., Lin, H. (2015). Material Speculation: Actual Artifacts for Critical Inquiry. Aarhus Series on Human Centered Computing

Wakkary, R. (2021). Things we Could Design: For more than Human-Centered Worlds. MIT Press.

Westerlaken, M., Gualeni, S., (2016). Situated Knowledges through Game Design: A Transformative Exercise with Ants. In Proceedings of The Philosophy of Computer Games. p.1-25. The Game Philosophy Network. http://hdl.handle.net/2043/22422

Wilson, E.O. (1984). Biophilia. Harvard University Press, Cambridge, MA.

Ana Schacht

→ MA graduate, with a BA in Integral Design from Pontifical Catholic University (CL) and an MA in Sustainable Design from Design School Kolding (DK). Lead author and designer of the case study mentioned in the paper. Her practice combines multi-disciplinary design approaches together with biology to configure new possibilities in the field of material innovation, design research and speculative design.

Sofie Kinch

→ Assistant professor, Ph.D., at the Lab for Design and Play and the Department of Textile Design at Design School Kolding (DK). With more than 10 years of experience in academia and design practice, her research concerns how we can allow each other to imagine our possible technological futures through design. Sofie works within the fields of playful learning and making with tech. She is particularly interested in how digital craftsmanship, speculation and play offer diversity and equality within education.

Designing matter across scales with microorganisms: The MMMM (Micro-Mezzo-Macro-Meta) approach

Sicher, Emma, Humboldt-Universität zu Berlin, Italy
Seçil, Uğur Yavuz, Free University of Bozen-Bolzano
Nitzan, Cohen, Free University of Bozen-Bolzano

Abstract

Biodesign is a growing discipline focusing on material futures, alternative production methods and more interdependent solutions with Nature. In particular, it fosters designers to interact with other microorganisms and living matter for the development of materials and potential applications often based on material tinkering and material-driven design methods (MDD). The interweaving of human and other-than-human agencies raises multiple questions and characterizes levels of complexity throughout the design process. The purpose of this article is to elaborate *a posteriori* on practice-based research to support biodesigners in their interdisciplinary practices.
First, it proposes "mattertypes" as a comprehensive term that describes material prototypes resonating with non-anthropocentric design. Mattertypes embody not only human and other-than-human agencies but also situated peculiarities: environmental, social, and systemic factors and implications.
Second, it illustrates an approach called MMMM (Micro-Mezzo-Macro-Meta) a scale-based structure that aims to facilitate project workflows and enhance the understanding of the whole process. The scales are explained with practical examples based on the experience gathered during three research projects on SCOBY [1] (also called bacterial or microbial cellulose). Namely, a product design BA- and an Eco-Social design MA-thesis, and an interdisciplinary research project investigating and developing packaging, food concepts, and scenarios for more resilient (g)local prospects.

Biodesign, prototyping, DIY materials, bacterial cellulose, glocalism

The active engagement of design disciplines with microorganisms has been emerging in the last decades. Biodesign (Myers, 2012) is the name of the field of reference encompassing approaches such as growing design, in which existing microorganisms like bacteria, fungi, microalgae, or mixed cultures are used for researching and developing new sustainable materials (Camere and Karana, 2017). Microbial production is used to generate substances that have peculiarities differing from established materials with foreseeable behaviours, characteristics, and performances. In this realm, material making and processing protocols – also called 'recipes'- are investigated and defined using Material-Driven methods and material tinkering seeking to achieve interesting properties and qualities revealing new material experiences (Karana, et al. 2015; Parisi, et al. 2017). Iterative sessions result often in high amounts of samples, models, and prototypes acting as tangible proof of processes

[1] Symbiotic Culture of Bacteria and Yeasts also known for being a cellulose-based pellicle with remarkable properties, edible and non-edible potentials

(Rognoli and Parisi, 2021). In the R&D processes of DIY materials, designers encounter uncertainty, failures, unforeseen discoveries, and surprising results, even more so when including living micro-entities and their own agencies. Given the high amount of variables and co-metabolic dynamics, it could be hard even for microbiologists to explain why outcomes might be different from what expected (L. Conterno[2], Personal communication, November 29, 2022).

Working with microbes is a highly experiential and embodied practice that is based on a certain degree of co-dependence and even on a sort of intimate relation. Hence, producing new materials does not depend solely on human agency anymore but is negotiated with other-than-humans towards multispecies design (Rognoli, Pollini and Alessandrini, 2021). The process involves getting to know the microbes, nurturing them, and acting according to their biological preferences -or not- depending on wished variables in the end outcome. Experts, tools, and methods from different fields are often involved in growing design projects, creating new relationalities and approaches that strive to propose sustainable practices on distributed, local, and global scales (Cohen, et al., 2022b), so-called (g)local (Robertson, 1995).

Drawing on practice-based experience gained in the course of ongoing interdisciplinary research projects investigating SCOBY, this paper proposes *a posteriori* elaborated terminology for prototyping and a holistic project approach based on scales that aims to facilitate project workflows and enhance the understanding of the whole process.

First, "mattertypes" is introduced as a comprehensive term describing material outputs of biodesign and material-driven projects. Mattertypes represent a shift towards a more dynamic, organic, and collaborative approach to design that interweaves human and other-than-human agencies with science, technology, society and environment.

Second, the 'MMMM' ('Micro–Mezzo–Macro-Meta') approach is proposed to tackle the high complexity of practice-based biodesign projects. By suggesting a scale-based structure, it aims to support biodesigners in assessing project workflows suggesting activities and collaborations, and enhancing an overall understanding of their practice.

Prototype in Designscapes

Prototyping is one of the fundamental designers' activities resulting in a variety of definitions, intangible solutions, tangible matters, and application proposals. Houde and Hill (1997) highlight the ambiguity of the meaning of prototype as a term in the different design fields that can range from a foam model to a storyboard. Furthermore, a prototype can be any representation of a design idea showing its 'role', 'look and feel', or 'implementation' (ibid). This ambiguity and variety have been increasing since design research as a field has been growing and evolving in diverse ways of doing and knowing. Shifting from a mere representation towards means of experimentation and inquiry, prototypes can be defined 'as vehicles for research about, for or through design' (Wensveen and Matthews, 2014). Research through design focuses on 'the possibility of design to be done on the basis of

---

[2] Dr. Lorenza Conterno is a microbiologist head of the Fermentation and Distilliation Group of the Laimburg Research Centre in South Tyrol

design practice i.e. by artistically/creatively making objects, interventions, processes etc. in order to gain knowledge' (Bang et al. 2012). Therefore, such 'procedural artifacts' differ from traditional prototyping of products and embrace social, conceptual, and ontological functions (Schubert at al., 2021).

Besides the role of artifacts as knowledge generators, they can also provoke debate and 'embody tensions surrounding an area of interest' (Boer and Donovan, 2021). Moreover, in design fiction, 'diegetic' prototypes acquire a different function 'to suspend disbelief about change' (Sterling, 2012) and make people experience possible futures through simulations of future scenarios and materializing not-yet-existing technologies.

In the wide designscape, prototypes are used in many ways and engage with diverse audiences, such as 'users' to test ideas, co-designers to make collective decisions (Houde and Hill, 1997), or a specific group of people –like neighborhoods- to foster social actions. Depending on the context and the engaged public, prototypes vary in role, form, and scale.

In emerging fields like biodesign and material-driven design, prototyping embraces new characteristics going beyond the above-mentioned functions. As Ferraris & Barzilai (2021) assert, such transcendence makes sense since 'things' that are at the center of the practice are living beings.

Prototyping materials: Mattertypes

Although prototyping in design research has been acquiring new roles and meanings, still in the traditional product design processes, the terms commonly utilized to describe objects, devices, materials, and artifacts that are developed are: models, and prototypes. This terminology is strongly linked with industrial mass production in which the development of a new product involves a series of iterations from concept, through 2D and 3D development and visualization of an artifact, to its material and production drafts, until the final evolved artifact is serially produced.

Often materials chosen for models are cheaper and easy to shape, simulate volumes, structures, colours, and surface finishings allowing designers to test and observe them, conduct user testing, discuss, and generate insights that enable development with valuable and advantageous adjustments. Prototypes are instead, often made using the same or similar materials and production techniques that are intended to be the final ones.

However, in the field of DIY materials, the focus is on the development of substances and matter that could only later be used for new applications and artifacts. Given that 'models' and 'prototypes' are generally made of already established materials in product design processes, such terminology could be limited as it does not refer specifically to materials.

Material-driven design and biodesign encourage more radical approaches to the very matter that could constitute artifacts with enhanced ecologic and systemic commitments. Material tinkering (Parisi, et al. 2017) especially, focuses on iterated samples that could further mature into new materials. Indeed, it could be seen as a pre-prototyping practice that fosters designing 'with materials' or 'for materials' (Rognoli and Parisi, 2021). Rognoli and Ayala-Garcia (2021) refer to DIY material samples developed in tinkering-for-materials processes as 'material drafts and demonstrators'. Especially, 'material demonstrators' aim to showcase the outcomes of material experimentation and their variants. They could be delivered to companies that could refine and finalize them for commercial applications or used for design speculations (ibid.).

From an ontological point of view, Bennett introduces ‘vibrant matter’ (Bennett, 2010) as a term expanding materiality to the vitality of the matter by highlighting its multiple agencies within complex ecologies. Moreover, a recent paper by Zhou, et al. (2022) illustrates material-centric approaches in which non-human actors are active contributors to the design process itself. In this way, materials become carriers of a wide variety of information reshaping human and other-than-human relations by embedding their agencies.

During our exploration of growing materials, we perceived a gap in the terminology to effectively articulate the nature of our work and its outputs. Therefore, we propose the term "Mattertype" merging “matter” intended as both “subject of the discourse”, and “substance from which something is made” with “type” intended as “kind”. It is a holistic term that resonates with non-anthropocentric design (ibid.) and could be used to describe material outputs of growing design and material-driven projects, meant as the various material prototypes that emerge through iterative work in a design process.

Mattertypes represent more dynamic, organic, and collaborative approaches to design based on materials that incorporate the agencies of humans and other-than-human entities. Mattertypes are seen as material entities within interdependent systems (assemblages). They have environmental, systemic, and social entanglements, and broader implications beyond just their physicality.

Mattertypes are organic substances, functional ingredients, based on biomasses. They can come in different states ranging from powder to granulate, to sheets, to blocks, to solid foam, to gels. They could be unprocessed or processed, precise cut-out samples as well as organically defined shapes, homogeneous or heterogeneous, smooth or rough, soft or hard, wet, humid or dry, quickly decomposing to durable, with different textures and aesthetics.

Methods for co-working with microbes

Material designers engaging with microbes often focus on production-driven innovation and likely use experimental approaches to design for regenerative systems. To do so, methods coming from different disciplines are adopted. Growing materials practices often use methods from ‘DIY material design’ (Rognoli, et al., 2015). However, tinkering is not only practiced with materials but also with the growth process. Indeed, different nourishing sources, parameters and growing conditions -such as temperature, humidity, acidity- can generate diverse properties and both, edible and non-edible potentials. Co-working with microbes is based on ‘learning-by-growing’ namely, the embodied and subjective experience of the ‘getting to know’ of the microbes by understanding how to create an environment where they can proliferate and thrive. Understanding includes also different senses (Rognoli, 2010) indeed, information about the state of growth could often be perceived through sight (color change of the growth medium, color of the growing microbial substance, textures and aesthetics of the microbial cultures), smell (acidic or basic could suggest the state of acidity and possible contamination), touch (toughness, fragility, density), and in some cases also taste.

The monitoring of the microbes can occur by combining qualitative and quantitative methods requiring both subjectivity (senses) and objectivity (data collection devices) throughout the process. Subjectivity is essential in the generation of intuitions, insights, hypotheses ranging from microbial growth, material experimentation and selection, prototyping and potential applications. Subjectivity does not only include human perspectives but alsoother-than-human expression and agency (Braidotti, 1994). Therefore, when talking about subjectivity, the microorganisms' own perspective, perception and modes of communication should be also taken into account as a different type of intelligence (Bridle, 2022).

Objectivity refers to measurements, data collection, and comparative methods taking place often in collaboration with scientists who share their know-how and enable access to equipped labs and machinery. In this way, it is possible to systematically address processes, test hypotheses and assess repeatable protocols for growing and post-growth processes, processing, evaluate variables, and effective potentials.

Similarly to material tinkering, also growing material practices borrow equipment and tools from other fields like craft, culinary, and biotechnology fostering cross-pollination among disciplines (Parisi, et al. 2017; Ayala-Garcia, 2015). When material-driven design meets biotechnology, the focus is often on the revalorization of resources that are currently discarded or undervalued proposing ways to recognize and enhance their value. Interestingly, when co-working with microbes, the borders between food and materials blur as microbial agencies could turn food into non-food and even into food again stimulating situated investigations to identify regenerative opportunities (Cohen, et al. 2020).

Methods and tools in biodesign are highly interdisciplinary as multiple factors, dimensions and scales come into play. This complexity leads not only to an urge to reflect upon iterative tinkering and prototyping activities but also upon methodologies to facilitate the assessment of design-driven projects in frameworks with multiple disciplines.

Prototyping across scales: ongoing R&D with SCOBY

SCOBY is a Symbiotic Culture of Bacteria and Yeasts that looks like a thick and translucent gelatinous pellicle (fig. 1). It is known for being the Kombucha starter: it is commonly immersed in sweetened tea, fermenting it into the popular beverage. During the brewing process, the microbes feed on the dissolved sugars and generate acetic substances and microbially produced fibers of pure cellulose generating a new pellicle. Besides the originally Manchurian drink (Villarreal-Soto, et al. 2018), this process is renowned also for Nata de Coco (fig. 2) which is a low calories and fibers-rich dessert popular in the Philippines (Piadozo, 2016). Nata is made of SCOBY obtained from the fermentation of a production 'byproduct': coconut wastewater. It is generally cut into cubes, cooked into syrups, and often served with fresh fruits.

Figure 1: SCOBY grown from sweetened tea *Figure 2: Nata de Coco (SCOBY grown from coconut wastewater)*

From a scientific perspective, the SCOBY is made of a matrix of bacterial cellulose (BC) nanofibers that are produced by acetic acid bacteria (AAB) -especially by *Komagataeibacter xylinus* (Serra and Hengge, 2019). These nanofibers are a hundred times thinner than those of plant cellulose, and their water-holding capacity is hundred times higher (Chawla, et al., 2009) –retained water constitutes more than 90% of the SCOBY volume. In addition, the pellicles possess valuable properties like high cristallinity and tensile strength, insolubility in water and most solvents, moldability, high degree of polymerization with a variety of possible material states and applications (ibid.). Interestingly, BC can be successfully produced also using fruit- and vegetable-based secondary products like pomace and marc (Pajuelo, et al. 1997; Kurosumi, et al., 2009; Islam, et al. 2017). This feature results in two main benefits: on one hand, functional and nutritional properties can pass from the nourishing liquid to the SCOBY thanks to the fibers' adsorbent characteristics (L. Conterno, personal communication, November 10, 2022) on the other hand, SCOBY production could have lower costs (Bungay, et al., 1997; Mohammadshirazi and Kalhor, 2016; Hussain, et al. 2019) and be adapted to different available biomasses, production scales and (g)localities.

Although plenty of ongoing research on BC is conducted, it is yet underexplored, especially with regard to possible material states, applications, and uses that go beyond SCOBY sheets, and especially, fashion-related and wound-dressing proposals.

New opportunities and potentials have been revealed during ongoing research focusing on SCOBY conducted at the Faculty of Design and Art of the Free university of Bozen-Bolzano. Namely, design-driven investigation was carried on with three consequent projects: 'From Peel To Peel' a Design BA thesis (Sicher, 2017), 'InnoCell' an interdisciplinary funded research 2018-2022 (Design F(r)iction Lab, 2023) and 'EATING SCOBY' an Eco-Social Design MA thesis (Sicher, 2022).

Throughout these projects, the process of prototyping was re-evaluated and seen as a range of tangible and intangible outcomes used to manifest design ideas.

These ideas were developed in different stages and sizes, aiming to create practical knowledge, mattertypes, prototype applications, and theories in the context of South Tyrol. This process required ongoing interdisciplinary collaboration with partners and stakeholders from various fields.

We realized *a posteriori* that such a multiscale and interdisciplinary approach enables not only theoretical speculation but also a deeper and more holistic learning process that promotes more conscious and grounded project development. Moreover, a systemic investigation in a situated context provides opportunities to directly interact with stakeholders, and address site-specific ecologic, social, and systemic issues.

The 'MMMM' (Micro-Mezzo-Macro-Meta) approach

The proposed R&D approach (fig. 3) is denominated 'MMMM' - Micro Mezzo Macro Meta. It suggests a project structure that intends to support biodesigners and interdisciplinary teams in organizing workflows and dealing with multiscale complexity. It is based on six years of highly experimental practice-based research in the realm of growing design projects that aim at speculating and benefiting existing (g)localities. The four proposed scales are explained with practical examples suggesting R&D tips, activities, possible collaborations, and outcomes.

In other words, the MMMM approach aims to facilitate the planning of projects involving multiple disciplines. This approach can be used not only to develop new materials but to implement a more holistic systemic perspective. Matter is seen as active element in a system of multiple-intersecting-scales rather than just a mere resource. The intent is also to foster a continuous understanding of what one is doing through ongoing discourse with actors and stakeholders. Such commitment aims at addressing urgent ecologic and social issues and developing feasible solutions based on existing realities.

Micro

The goal on this scale is to get closer to the microcosmos to identify microbial entities of interest, get to know their biology and frame their capabilities, needs, and potential to grow matter. This part requires an in-depth literature review involving not only design publications but also a variety of scientific disciplines (food technology, biology, microbiology, synthetic biology, chemical engineering, ecc.). Through this knowledge, designers would be able to learn specific scientific/technical language, test research questions, and plan microbial growth experimentations. Especially, it is important to learn about nourishment, equipment requirements, and possible variables conducting to different outcomes. This state-of-the-art research enables learning-by-growing and identify, hack, iterate, and define protocols for the growth and (re)production of microbial substances.

A combined subjective and scientific approach based on trial and error with a systematic collection of data is essential to enable efficient iterations and scale-ups (Rognoli and Parisi, 2021). Acquiring competencies about microbial growth is important for designers as it facilitates the maintenance of the microbes, successful yields, and an easier achievement of wished properties fostering more independence, less failure frustration, and dramatic time and resources saving.

For this research part, collaboration with interdisciplinary experts is strategic and strongly recommended. It is ideal to connect with people involved in disciplines ranging from material science to microbiology, bio- and food-technology. Academia and public institutions could provide more accessible knowledge, equipment, resources, and infrastructures. Sometimes, even open co-working spaces like FabLabs could dispose of suitable machines and tools. In some cases, these specialized workspaces are called Kitchen Labs as is the case at NOI Techpark, or BITZ fablab of the Free University of Bozen-Bolzano which offer mixed equipment commonly used in gastronomy and scientific labs. However, also private practitioners and centers could offer valuable support and knowledge-sharing could be more limited, often due to NDAs.

Figure 3: Visualization of the MMMM method and its core points

The research on SCOBY began with the intention to tackle ecologic issues around single-use packaging. SCOBY was chosen among other actors such as algae, and DIY bioplastics because of its capacity to be produced using locally discarded biomasses and its adaptability to various raw resources. These characteristics make it very versatile and possible to implement in many local areas around the world. In the beginning, the growth and consequent experimentation on SCOBY were conducted without a structured methodology. It soon became clear that a systematic workflow and collaboration with scientific partners would have improved the growth process. Therefore, a collaboration began with food technology experts (Food Technology platform, Faculty of Science and Technology – unibz) who supported in setting the parameters to prepare nourishing medium and methods to monitor and adjust it during the growth. This collaboration continued throughout the 'InnoCell' project. In such a framework, the food technologists tested, compared, and analyzed nourishing liquids for SCOBY growth based on tea, lemon-marc, and apple pomace (unpublished results) to define efficient and reproducible protocols. They were then provided to the design team that, after learning how to use specialized equipment and perform them, independently took over the production of SCOBY mass. The generated amounts were then used to tinker and iterate mattertypes aimed at developing application prototypes.

During InnoCell, samples of the produced SCOBY mass were delivered to another team of experts namely, microbiologists (Micro4DFood team, Faculty of Science and Technology – unibz) who conducted comparative tests regarding the impact of bacterial cellulose fibers on microbiota under simulated gastrointestinal conditions. The preliminary unpublished results show that SCOBY grown from apple-pomace embeds valuable antioxidants (arabinoxylans). This unexpected finding together with published scientific articles (Shi, et al. 2014; Azeredo, et al., 2019; Vitas, et al. 2020) supports the nutritional potential of SCOBY as a prebiotic food source. This seed information was the ground for the MA thesis project 'EATING SCOBY' which framework involved a strict collaboration with microbiologists (Fermentation and Distillation Group of Laimburg Research Centre). It resulted in protocols defining nourishing liquid preparation with four different biomasses produced in South Tyrol (apple, raspberry, beetroot, grapes) and conducted a comparative analysis (fig. 4-7) about antioxidant potential and total polyphenol content (TPC) that confirmed the prebiotic potential of all four generated SCOBYs. This result provided scientific confirmation that grounded and improved the credibility of hypothesized applications and scenarios.

Fig. 4 SCOBY grown from local secondary products-based liquids at Laimburg Research Centre.

Fig. 5 Powder samples of the grown SCOBYs.

Fig. 6 SCOBY extracts made for antioxidant analysis at Laimburg Research Centre.

Fig. 7 Plate prepared with extracts for antioxidant analysis at Laimburg Research Centre.

Mezzo

Mezzo focuses on material-driven design (Karana, et al. 2015), tinkering, mattertypes, and prototyping.

Production equipment and tinkering

Once the growth process is mastered and the wished substance is produced in good quantity, the following goal is often to actively achieve new materials (Ribul, 2013; Rognoli and Ayala-Garcia, 2018) with unique capabilities that ideally overcome the notion of 'material surrogates' (Rognoli and Levi, 2005). (Microbial) Matter can be used with a 100% concentration and/or be mixed with other functional substances that enhance the performances. Tinkering often involves dying and color effects, texturization, folding, forming (thermal and cold), casting, molding, stamping, foaming, extrusion, laser-cutting, and burning. However, the variety and quality of mattertypes are strongly dependent on the available equipment and accessible experimentation spaces. Often, designers (co)develop their own tools and equipment to achieve specific and/or preferred outcomes (Parisi, et al. 2017) ranging from hand tools to even high-tech bioreactors.

In project From Peel To Peel, SCOBY was grown in a static way with often improvised nourishing liquid. It soon became evident that such conditions were not ideal in terms of homogeneity of the medium, contamination potential and temperature variability. Therefore, the following growing cultures were hosted in an incubator in a food-technology lab which enabled constant monitoring and more controlled settings. During the project InnoCell, production processes were investigated through literature review and one appeared as the most efficient one in terms of liquid:generated SCOBY ratio namely, the rotating disks bioreactor. Such a principle was found in an expired patent (Bungay and Serafica, 1995) and scaled-up in an open-source module called the 'InnoCell Bioreactor' (fig. 8) (Cohen, et al, 2022a) enabling the production of 10 to 15kg of wet biofilm per production cycle (12-21 days) depending on nourishing source. Produced mass was later on used for tinkering and prototyping.

A suitable tinkering space needs to be well planned and established with enough usable surfaces, appliances for tinkering (generally a mix of kitchen tools (Ayala-Garcia, 2015) and lab equipment) and also in terms of safety measures and ventilation. It is also important to foresee where to store ingredients, experiments, and mattertypes. Labs commonly used in other disciplines (like biotechnology, gastronomy, and engineering) could also be used for collaborative tinkering, testing, and analyzing.

During the sessions it is essential to document procedures in a systematic way, this enables reproduction of mattertypes, easy adjustments towards preferred characteristics, and promotes insights generation for further experimentation. Partnering with scientists could provide planning and iteration insights, mutual learning processes, and promotes the development of a common language. In the MMMM approach, at a certain point in the tinkering process, mattertypes need to be selected to further develop prototypes.

In InnoCell the SCOBY mass (fig. 9) was produced with the bioreactor using media based on tea and on apple-biomass. Consulting scientific articles from engineering, biotechnology, food technology, and methods used in gastronomic disciplines like food rheology and

molecular gastronomy enabled the iterative development and finalization of techniques to transform SCOBY in different states. Tinkering and prototyping took place in design workshops and scientific laboratories (FaST Lab - unbz) and included processes like purification (fig. 10, 11), pulverization (fig. 12), transformation into granulate (fig. 13), sheets with various textures (fig. 14) and shades (fig. 15), and solid foam (fig. 16, 17). It was observed that depending on the nourishing source, processes and material recipes had to be adjusted differently.
It was generally observed that tea-grown SCOBY is more structural, tough and translucent while apple-based SCOBY is softer and more opaque.

In ‘EATING SCOBY’ techniques borrowed from gastronomy like deep frying, spherification, and jellifying were also implemented to develop food concepts.

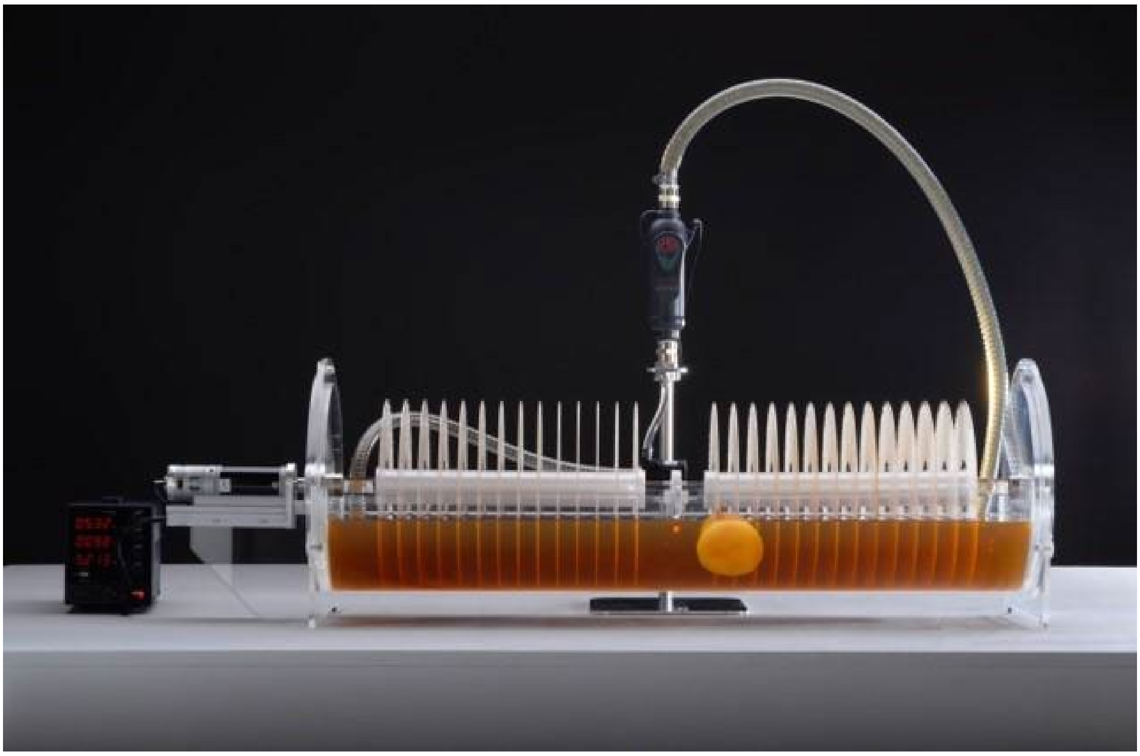


Fig. 8 InnoCell Bioreactor

Fig. 9 Harvested SCOBY grown with the bioreactor

Fig. 10 Purified wet biofilms

Fig. 11 Purified dry SCOBY sheet samples

Fig. 12 Mattertypes: Microbial cellulose powder

Fig. 13 Mattertypes: Microbial cellulose granulate


Fig. 14 Mattertypes: Patterned SCOBY sheets


Fig. 15 Mattertypes: Sheets dyed with different pigments

Fig. 16 Mattertypes: 100% SCOBY solid foam


Fig. 17 Mattertypes: Pigmented SCOBY solid foams

Prototyping

Prototyping is seen as the phase in which application hypotheses are materialized. First, to hypothesize possible applications it is essential to carry out in-depth interdisciplinary research defining a state-of-the-art of what has been done so far with the (microbial) substances in question. Such an inquiry is generally based on desk research and should navigate through design, scientific, and other case studies coming from different disciplines (gastronomy, engineering). This promotes building upon the existing knowledge and enables the identification of opportunity areas. Indeed, some novel discoveries made on laboratory scales have yet underexplored product and scale-up potentials. Possible applications can be generated with design thinking methods and co-design workshops. The involvement of interdisciplinary partners and stakeholders is encouraged to enrich the project with insights and know-how directly from gained experience, ongoing research, existing practices, and contexts.

Applications can be defined on the base of mattertypes' properties and performance, effective production possibility, or could also be highly speculative, depending on the project's intentions. As highlighted in the previous section, access to professional equipment and facilities is crucial and strongly affects the prototyping phase as well. Depending on available infrastructures, the applications can be materialized as models or prototypes to deliver the proposed potential visually and physically. Models could be made with alternative yet similar materials that are easier to collect or process. Prototypes, on the other hand, should be made using the selected mattertype recipes. However, at times the shaping or production process to make the prototype might differ from the technique that would be used for the possible scaled-up production of the matter.

In the project From Peel To Peel, research began by deepening the design-led work of Suzanne Lee (2011), Sacha Laurin (2015), and Ellen Rykkelid (2016). The latter project revealed the potential of SCOBY to be grown from fruit and vegetable sources that inspired the (g)local vision. The project's outcomes are prototypes of packaging bags and single-use containers (fig. 18). The main research question was: 'What if packaging could be made through regenerative production?'. Therefore, SCOBY was used to turn peels (secondary products) into other 'peels' (food packaging/containers) with similar life cycles. Single-piece prototypes were made in design workshops with SCOBY sheets processed in different ways.

In project InnoCell, possible SCOBY uses were brainstormed during design-thinking workshops also in collaboration with food technology experts. The selection of application hypotheses for prototyping was done according to the most innovative discoveries namely, the prebiotic potential of SCOBY and the newly developed solid-foam protocol.

Especially, the latter was not previously achieved in the design field so, its valuable potential was speculated as a compostable alternative for foam packaging like filling chips, and mono-material containers for electronic devices (fig. 19, 20) (smartphones, smartwatches, and earpods). These concepts were materialized with milled polyurethane models in design workshops.

The second direction was food, supported by data provided by microbiology colleagues confirming the antioxidant and prebiotic potential of SCOBY. Also in this case, the selected applications namely crackers (fig. 21) and chips were realized with milled polyurethane models while puffed crisps (fig. 22) were simulated with painted 3D-printed pieces. The reason for choosing models was because of time issues and technique, as milling was still to be tested on SCOBY foam volumes.

In the project EATING SCOBY, all artifacts were prototypes made with selected mattertype protocols materialized in design workshops, fablab (BITZ), and scientific labs (FaST Labs - unibz). Very valuable was the consultancy and collaboration with gastronomy expert chefs (Michelin starred Terry Giacomello and Michele Granuzzo) who suggested techniques to achieve specific material states and textures. The final prototypes resemble familiar designs like edible paper, chips, ice-cream cones, jelly candies, and pasta (flat, extruded-looking, fig 23; and filled, fig. 24), popsicles (fig. 25), puffed biscuits, puffed crisps, and snacks; and other specialized designs that are based on SCOBY's unique properties like oxygen barrier capability (sausage casing, fig. 26; sauce packets), its raw prebiotic, antioxidant and fibres-rich capabilities (jelly sphere dressing, fig. 27; and puffed supplements, fig.28 - that can provide also aesthetic qualities to the foods they are added to), and color possibilities, indeed, gradients and, colour effects can be easily obtained thanks to its hydrophilic characteristic.

After the physical realization of prototypes, visual documentation with high-quality pictures and videos is highly recommended as microbial matter is organic and inevitably oxidizes and decomposes over weeks or months. These aspects need to be planned in advance when aiming at producing exhibition materials: either mattertypes and/or prototypes are left to decompose, or are continuously (re)produced, it is suggested that visual documentation of the matter should be displayed as well to show the passing of time.

Fig. 18 Prototypes: From Peel To Peel | Bag packaging and single use tableware

Fig. 19 Models: InnoCell | Pods packaging

Fig. 20 Models: InnoCell | Packing chips

Fig. 21 Models: InnoCell | Puffed crackers

Fig. 22 Models: InnoCell | Puffed crisps

Fig. 23 Prototypes: EATING SCOBY| SCOBY radiatori

Fig. 24 Prototypes: EATING SCOBY | Gradient dumpling

Fig. 25 Prototypes: EATING SCOBY | Popsicle

Fig. 26 Prototypes: EATING SCOBY| Sausage casing

Fig. 27 Prototypes: EATING SCOBY | Sphere dressing

Fig. 28 Prototypes: EATING SCOBY | Puffed supplements

Macro

The macro level refers to the project's situatedness, it encourages to choose existing context(s) and investigate existing production systems by including also with local actors and stakeholders.

DIY materials and Material-Driven Design often aim at improving the use of resources to promote circular dynamics. In the MMMM approach, it is encouraged to conduct inquiry through desk and field research consulting reports, conducting interviews, questionnaires, and talking with experts, producers, research centers, institutions, and municipal administrations. Consulting and collaborating with people from social studies and humanities would be strategic for assessing efficient tools for field research.

It is especially strategic to choose a circumscribed geographical area as a case study (such as a region) and research its existing production and disposal systems. A special focus should be given to agri-food industries, which discarded secondary products are often suitable for microbial regeneration. In this way, the biomasses could be repurposed to obtain valuable upcycled edible and non-edible substances. Situated inquiry facilitates the identification of research gaps and opportunities. Moreover, it stimulates scenarios generation based on existing realities. Also, integrated, interdependent, resilient strategies could be ispired by other regional, national, and international case studies (glocalism). Doing so provides an enhanced systemic understanding enabling to more effectively ground the project.

Data, and flows can be represented with the aid of infographics, maps, or schemes (fig. 27). These tools can be used as a base for reflections, discussions, brainstorming, speculations, together with speculative design, design fiction, and fabulation methods. Preferable scenarios (Dunne and Raby, 2013; Haraway, 2013) could be co-designed embedding different scales and intentions: from effective implementation-driven collaborations with stakeholders to mere speculation; from a single case of study to systemic proposals suggesting new collaborations in existing networks; to versatile formulas that aim at fostering a (g)local impact. Design scenarios are useful means to present the project to stakeholders for testing feasibility and stimulate iterations, and/or for applying for additional R&D funding.

In the framework of all SCOBY projects, the chosen context was South Tyrol. While in From Peel To Peel and EATING SCOBY the focus was on prposals that could be implemented regionally, in InnoCell the intention was to develop tools, applications and formulas that could be glocally applicable.

Especially, in From Peel To Peel a selection of local secondary products was made focusing on locally-produced crops namely apples, potatoes, hops, beetroot, and grapes to envision possible nourishing sources. The provincial administration responsible for regional waste management was interviewed to understand flows within the system, and a plant for the disposal of urban organic waste was visited. According to the data collected, two scenarios were developed, one envisioning a SCOBY pilot-plant production within the existing facility (fig. 29) while the other speculated an independent facility.

In the framework of the project EATING SCOBY, fifteen local food-processing industries were contacted and asked to provide data about their secondary products. According to the replies, data were collected in an overview table and a selection of four typologies was done together with a partner microbiologist based on valuable substances still present in the biomasses (Dr. Lorenza Conterno, Fermentation and Distillation Group, Laimburg Research Centre). The selected nourishing sources were apples, raspberry, beetroot, and grapes. SCOBY was grown from prepared liquid media and analyzed confirming its valuable food-application potential. A system map including SCOBY as an actor (fig. 30) was designed gathering stakeholders and institutions, social, ecologic, and economic factors suggesting possible interactions and future collaborations with different scale and network possibilities (fig. 31). To conclude, an impact circle map (method developed by Corinna Sy) was realized to show possible dimensions of value creation (fig. 32).

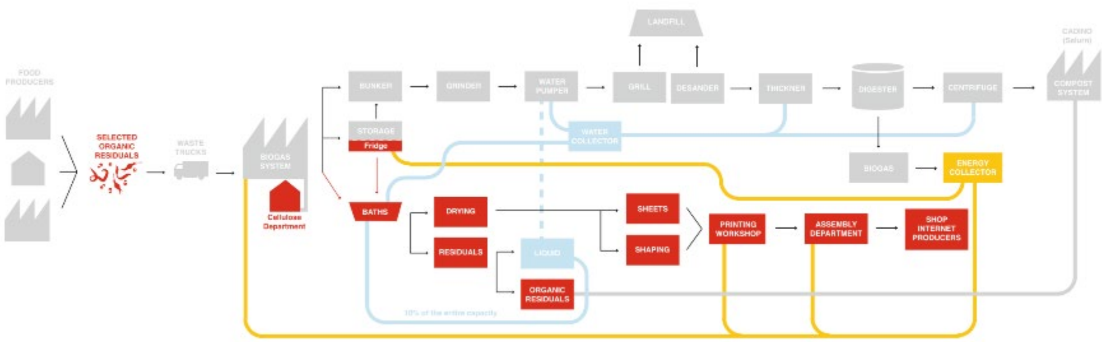


Fig. 29 From Peel To Peel project | SCOBY pilot production plant (in red) integrated into existing waste disposal facility

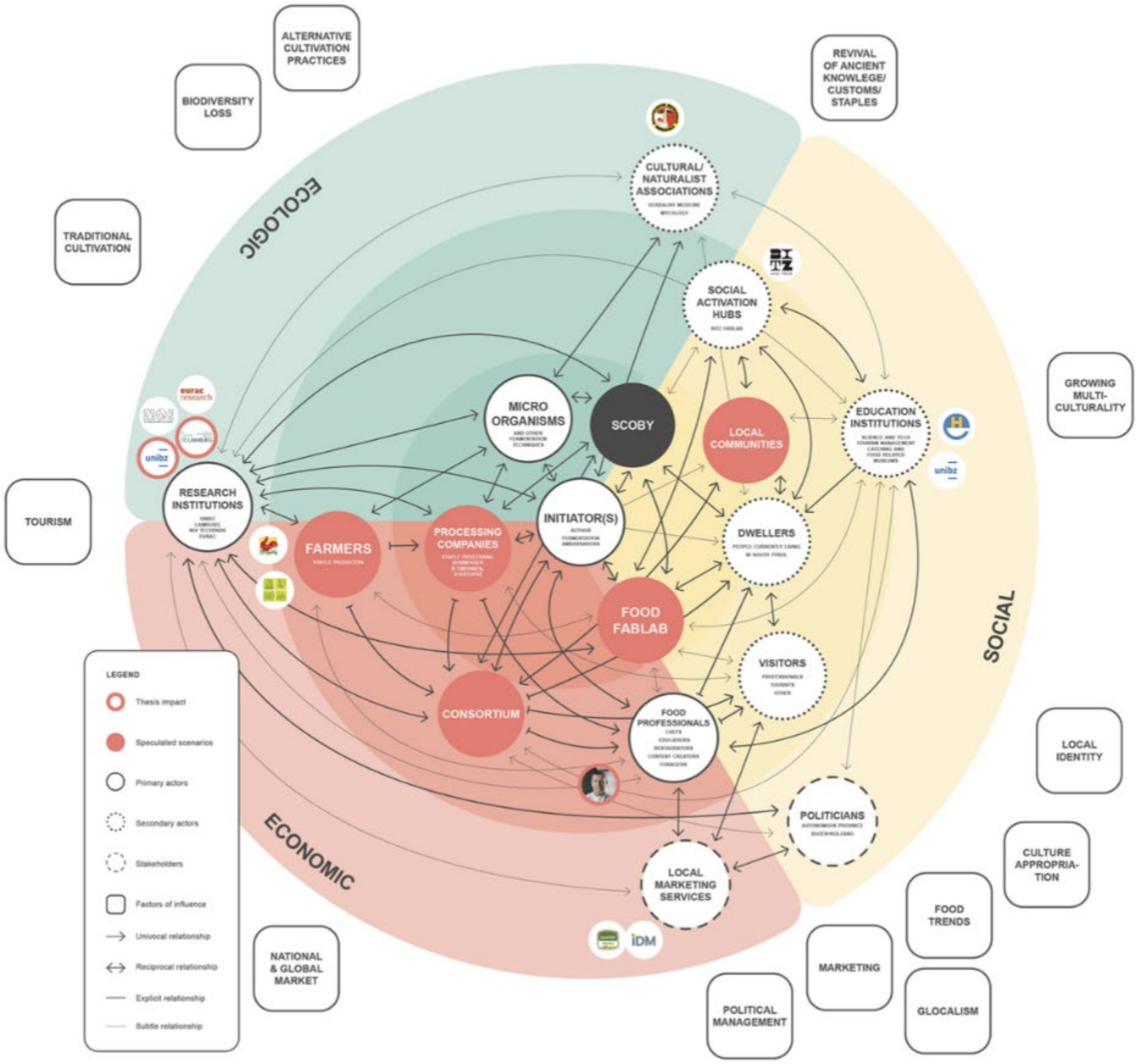


Fig. 30 EATING SCOBY project | Eco-socio-economic stakeholders map

SCENARIOS SUM-UP

who	activities	scenario possibilities	why
COMPANIES	FRUIT/VEGETABLES PROCESSING	Have coproducts know-how → implementation of SCOBY fermentation	→ new revenue streams → more circular economy → lower fixed costs
	POTENTIAL COLLAB		
	KOMBUCHA PRODUCTION	Have SCOBY fermentation know-how → implementation of coproducts fermentation	
POTENTIAL COLLAB			
CONSORTIUM	REFERENCE INSTITUTION management / education / facilitation / support	→ implementation of biomasses collection service for farmers and companies → implementation of SCOBY fermentation facility	→ increase farmer livelihoods' resilience (redistribute revenues) → enhance the value of primary resources → more circular economy
POTENTIAL COLLAB			
FARMERS	FRUIT PRODUCTION AND PROCESSING	Have coproducts know-how → implementation of SCOBY fermentation equipment	→ new revenue streams → more circular economy → personal consumption
FOOD-FABLAB	DEMOCRATIZED MAKING-PRODUCTION KNOWLEDGE	HI-TECH know-how → implementation of FOOD production and (SCOBY) fermentation equipment	→ knowledge and specialized machinery democratization → personal consumption
POTENTIAL COLLAB			
FARMER / FERMENTER	SMALL BATCH FERMENTATION	SCOBY fermentation know-how → implementation of SCOBY fermentation with household coproducts	→ personal consumption → 0 waste

→ opportunity

Fig. 31 EATING SCOBY project | Production scenarios scheme

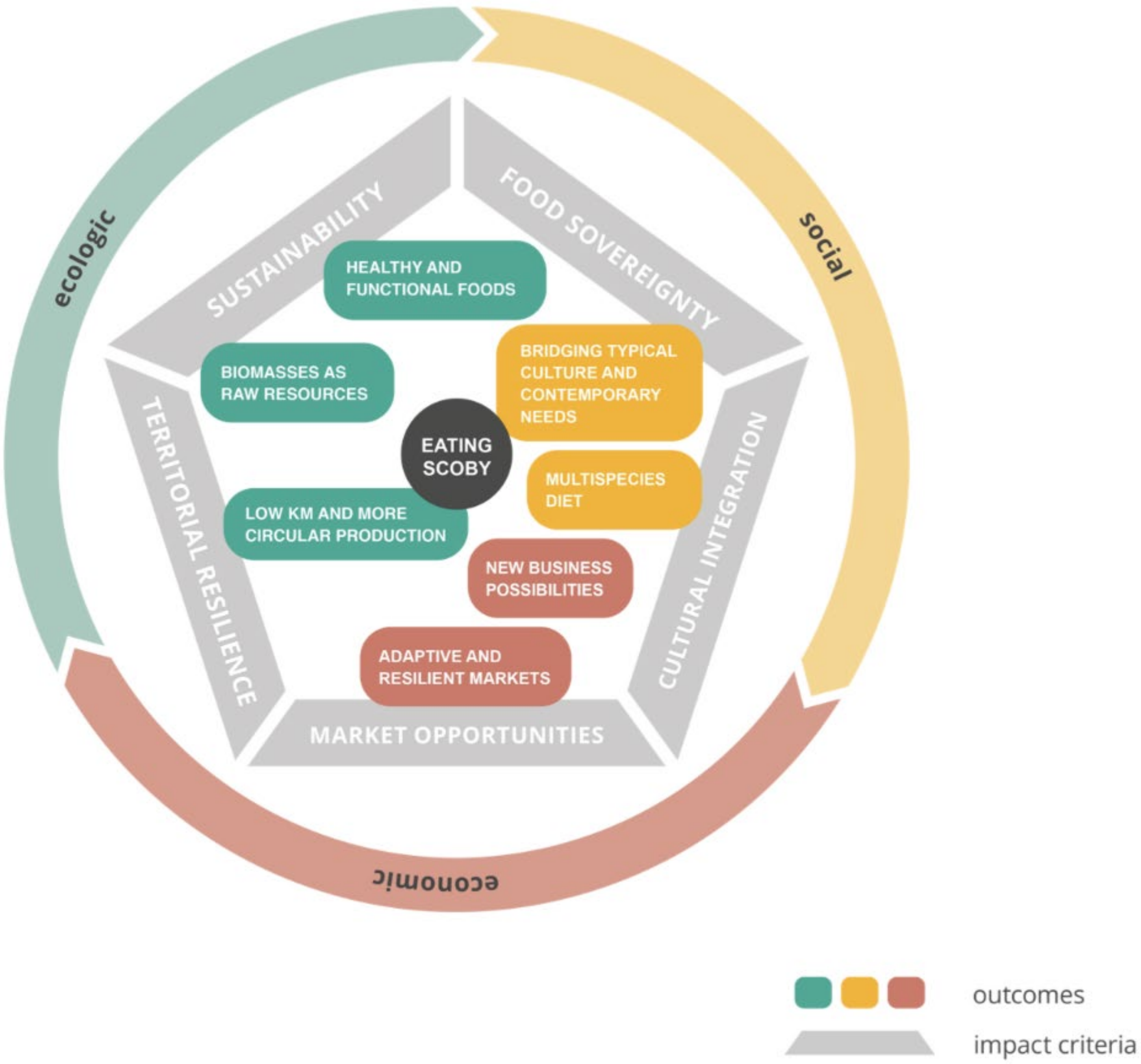


Fig. 32 EATING SCOBY project | Impact circle (by Corinna Sy)

Meta

The Meta level differs to the other three levels because it refers to the theoretical and practical knowledge that originates throughout the whole project. It likely becomes manifest through *a-posteriori* reflections and elaborations. While the Micro, Mezzo and Macro focus on case studies such as SCOBY, specific resources and situatedness, the Meta is about the generated knowledge that discusses and/or enriches ways to research through design.

This level resonates with Manzini's notion of Metadesign (2007) intended as the design of methodologies to support designers in a variety of design processes; and with Wood's interpretation as a framework to stimulate paradigm change in society and in dealing with design problems (2011). Especially, we refer to those principles, notions, and methods that originate from the practice-based investigation and are ongoingly iterated also by continuous discourses with stakeholders. The relevance of this newly generated knowledge goes beyond the single disciplines and sets new bases for following/future projects. Setting the

Meta as a level to be aware of enables to recognize and elaborate generated knowledge to enrich future R&D in the design process and approach, and their implications.

Within our ongoing research on SCOBY, the Meta level was especially elaborated during and after project InnoCell.

First, by reflecting on the non-existence of waste in the microbial world we proposed a production paradigm that substitutes ‘product and byproduct’ with ‘meta-product and co-products’ (Cohen, et al. 2022b). Meta-product refers to a raw resource that is processed into a variety of substances (co-products) that can either be ‘products’ themselves or initiate other regenerative production process, coherently with the cradle-to-cradle philosophy (McDonough and Braungart, 2010). This was inspired by the case of an apple that could be processed to obtain the juice while the peels and cores could undergo SCOBY fermentation generating multipurpose SCOBY mass, a fermented liquid (drink or vinegar), and very little biomass that can be used as prebiotic fertilizer.

In addition, a project pattern was framed highlighting the potential of using different lenses going from local to global and vice-versa to promote the potential of (g)local formulas (Robertson, 1995) to stimulate local resilience. ‘Biocouture’ project by Suzanne Lee raised a discourse about alternative sustainable production and inspired From Peel To Peel to focus on a local scale while InnoCell brought the discourse on a (g)local level through the open-source bioreactor and the development of SCOBY mattertypes. This pattern (fig. 33) could be used also with other microorganisms and transform local case studies into (g)local formulas that could benefit other local areas around the world.

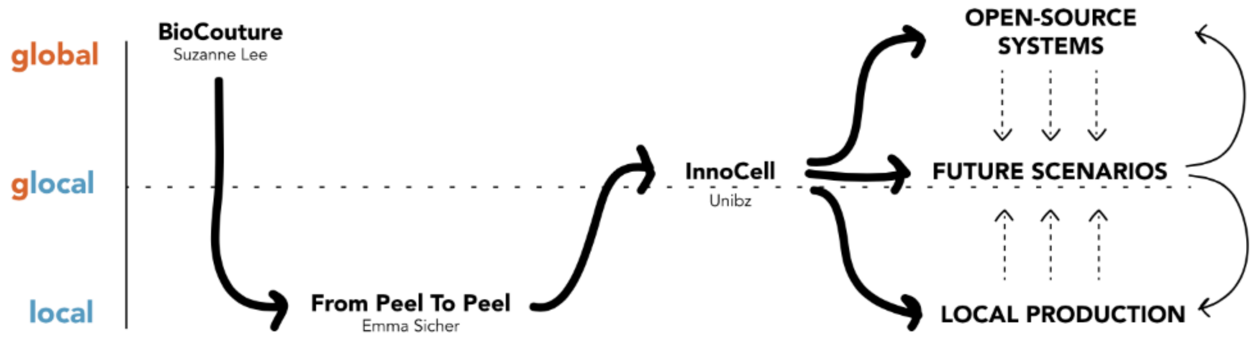


Fig. 33 InnoCell project | Project pattern in Cohen et al. (2022)

From a practice-based design perspective, partnering with local experts and stakeholders sets the base for future collaborations. In particular, cooperating with scientists enables to acquire competencies that speeds up future processes going from the assessment or microbial growth conditions to processing, modelling and prototyping.

This article, by introducing the term Mattertypes and the MMMM approach, is itself part of the Meta-level of ongoing SCOBY research.

To conclude, this scale encourages elaborating on the gained knowledge to create a valuable blueprint for supporting ongoing and future projects.

Conclusion

This article describes contributions in the matters of terminology and project approach that were elaborated *a-posteriori* of ongoing practice-based interdisciplinary design research with a focus on growing design.

In order to enrich and expand meanings and scopes attributed to material research and activities of model making and prototyping, the new term 'mattertype' is introduced referring to DIY material prototypes that embed human and other-than-human agencies. Moreover, mattertypes are seen as entities interwoven in interdependent systems.

Based on six years of practice-based research, this manuscript proposes a multi-scale perspective that aims at facilitating the planning and workflow of design projects involving living matter and DIY materials. The Micro-Mezzo-Macro-Meta approach (MMMM) serves not only as a support to develop theoretical and practical knowledge related to growing design; but it also highlights the value of including interdisciplinary knowledge, stakeholders and systemic prospects. As such, it encourages the inclusion of ecologic, social, and systemic aspects to generate plausible scenarios in situated contexts.

With the illustrated examples, the intention is to suggest how microorganisms and their high adaptability could be combined with unique local conditions to enhance interdependence and cater for valuable strategies of resilience. Indeed, working with microbes stimulates designers to consider multispecies agencies and to translate such principles across scales towards regenerative processes.

We are confident that the MMMM approach will not only bolster our future endeavours, but also inspire fellows to embrace multispecies design and non-anthropocentric approaches for promoting sustainable and regenerative (g)local practices.

References

Ayala-Garcia, C. (2015). The Basis of Processes - Experimenting with Food to Re-Shape the Industry Language. In: Proceedings of Cumulus Conference, The Virtuous Circle: Design Culture and Experimentation. Milan: McGraw-Hill Education

Azeredo, H., Barud, H. S., Farinas, C. S., Vasconcellos, V. M., & Claro, A. M. (2019). Bacterial cellulose as a raw material for food and food materials packaging applications. Front Sustain Food Syst.

Bang, A. L., Krogh, P., Ludvigsen, M., & Markussen, T. (2012). The role of hypothesis in constructive design research. In Proceedings of the Art of Research IV.

Bennett, J. (2010). Vibrant matter: A political ecology of things. Duke University Press.

Boer, L., & Donovan, J. (2012, June). Provotypes for participatory innovation. In Proceedings of the designing interactive systems conference (pp. 388-397).

Braidotti, R. (1994). Nomadic subjects: Embodiment and sexual difference in contemporary feminist theory. Columbia University Press.

Bridle, J. (2022). Ways of being: Beyond human intelligence. Penguin UK.

Bungay, H.R., Serafica, G.C. (1995) US5955326A, United States.

https://patents.google.com/patent/US5955326?oq=US5955326A. Accessed 28/04/23

Bungay, H. R., Serafica, G., & Mormino, R. (1997). Environmental implications of microbial cellulose. In Studies in Environmental Science, 66, pp. 691-700

Camere, S., & Karana, E. (2017, June). Growing materials for product design. In Alive. Active. Adaptive: Proceedings of International Conference on Experiential Knowledge and Emerging Materials (EKSIG 2017) (pp. 101-115).

Chawla, P. R., Bajaj, I. B., Survase, S. A., & Singhal, R. S. (2009). Microbial cellulose: fermentative production and applications. Food Technology & Biotechnology, 47(2), pp. 107–124.

Cohen, Nitzan, Sicher, Emma and Uğur Yavuz, Seçil (2020), 'Designing with microbial cellulose to feed new biological cycles1', International Journal of Food Design, 4:2, pp. 155–171, doi: https://doi.org/10.1386/ijfd_00003_1

Cohen N., Sicher E., Merino I., Yavuz S.U. (2022)a An Open-Source Bioreactor Enhancing Microbial Cellulose Production and Novel Sustainable substances. In: Scholz S.G., Howlett R.J., Setchi R. (eds) Sustainable Design and Manufacturing. KES-SDM 2021. Smart Innovation, Systems and Technologies, vol 262. Springer, Singapore.https://doi.org/10.1007/978-981-16-6128-0_8

Cohen N., Sicher E., Uğur Yavuz S. (2022)b From Agricultural Waste to Microbial Growth and (G)Local Resilience. In: Duarte E., Rosa C. (eds) Developments in Design Research and Practice. Senses 2019. Springer Series in Design and Innovation, vol 17. Springer, Cham. https://doi.org/10.1007/978-3-030-86596-2_7

Design F(r)iction Lab (2023) https://designfrictionlab.com/ Last accessed 28/04/2023.

Dunne, A., & Raby, F. (2013). Speculative everything: design, fiction, and social dreaming. MIT press.

Ferraris, S. D., & Barzilai, G. (2021). The evolving role of prototypes in design research: a discussion on terms and meanings. In Cumulus Roma 2021 conference (pp. 1825-1839). [Espoo]: Aalto University.

Haraway, D. J. (2013). SF: Science fiction, speculative fabulation, string figures, so far.

Houde, S., & Hill, C. (1997). What do prototypes prototype?. In Handbook of human-computer interaction (pp. 367-381). North-Holland.

Hussain, Z., Sajjad, W., Khan, T., & Wahid, F. (2019). Production of bacterial cellulose from industrial wastes: a review. Cellulose, 26(5), pp. 2895-2911.

Islam, M. U., Ullah, M. W., Khan, S., Shah, N., & Park, J. K. (2017). Strategies for cost-effective and enhanced production of bacterial cellulose. International Journal of Biological Macromolecules, 102, 1166-1173.

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences.

Kurosumi, A., Sasaki, C., Yamashita, Y., & Nakamura, Y. (2009). Utilization of various fruit juices as carbon source for production of bacterial cellulose by Acetobacter xylinum NBRC 13693. Carbohydrate Polymers, 76(2), 333-335.

Laurin, S. (2015) Kombucha Couture. [Website]. Retrieved from: http://www.kombuchacouture.com/ Last accessed 28/04/23

Lee, S. (2011) Grow your own clothes. TED Talk. Retrieved from: https://www.ted.com/talks/suzanne_lee_grow_your_own_clothes Last accessed 28/04/23

Manzini, Ezio. 2007. 'Designing Networks and Metadesign'. Attainable Utopias [online]. Available at http://attainable-utopias.org/tiki/ManziniMetadesignNotes. Last accessed 14/04/23

McDonough, W., & Braungart, M. (2010). Cradle to cradle: Remaking the way we make things. North point press.

Mohammadshirazi, A., & Kalhor, E. B. (2016). Energy and cost analyses of kombucha beverage production. Renewable and Sustainable Energy Reviews, 55, pp. 668-673.

Myers, W. (2012). Bio design. Museum of Modern Art.

Pajuelo, M. G., Bungay, H., Hogg, T., & Vasconcelos, I. (1997). Lowering costs of microbial cellulose.

Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. The Design Journal, 20(sup1), S1167-S1184.

Piadozo,M.E.S. (2016). Nata de coco industry in the Philippines. In: Bacterial Nanocellulose: From Biotechnology to Bio-Economy, pp. 215–229

Ribul, M. (2014). Recipes for Materials Activism. Retrieved from: https://issuu.com/miriamribul/docs/miriam_ribul_recipes_for_material_a Last accessed January 5, 2023

Rykkelid, E. (2016), ‘Growing products’, 16 May, Diploma project at Oslo School of Architecture and Design, http://www.ellenrykkelid.com/portfolio/2910/. Last accessed 28/04/23

Robertson, R. (1995). Glocalization: Time-space and homogeneity-heterogeneity. Global modernities, 2(1), 25-44.

Rognoli, V., & Ayala Garcia, C. (2018). Material activism. New hybrid scenarios between design and technology. Cuadernos del Centro de Estudios en Diseño y Comunicación. Ensayos, (70), 1-3.

Rognoli, V. (2010). A broad survey on expressive-sensorial characterization of materials for design education.

Rognoli, V., & Ayala-Garcia, C. (2021). Defining the DIY-Materials approach. In Materials Experience 2 (pp. 227-258). Butterworth-Heinemann.

Rognoli, V., Bianchini, M., Maffei, S., & Karana, E. (2015). DIY materials. Materials & Design, 86, 692-702.

Rognoli, V.; Levi, M. (2005). Materiali per il design. Espressività e sensorialità. Milano: Polipress.

Rognoli, V., & Parisi, S. (2021). Material Tinkering and Creativity. Retrieved from:

https://re.public.polimi.it/retrieve/ e0c31c10-c583-4599-e053-1705fe0aef77/ Rognoli%201_MaDe-Book.pdf. Last accessed October 13, 2022

Rognoli, V., Pollini, B., & Alessandrini, L. (2021). Design materials for the transition toward post-Anthropocene. In FROM HUMAN-CENTERED TO MORE-THAN-HUMAN DESIGN Exploring the transition (pp. 101-130). Franco Angeli International.

Schubert, J., Ugur Yavuz, S., & Fuad-Luke, A. (2021) Procedural artifacts for design inquiry, Disegno Industriale Industrial Design, diid, #71. ISBN 9788832080506, pp.122-129

Serra, D. O., & Hengge, R. (2019). Cellulose in bacterial biofilms. Extracellular Sugar-Based Biopolymers Matrices, 355-392.

Shi, Z., Zhang, Y., Phillips, G.O., Yang, G.(2014) Utilization of bacterial cellulose in food. Food Hydrocolloids 35, pp. 539–554

Sicher, E. (2017), 'From Peel to Peel: An experimental design approach for packaging', BA thesis, Bozen-Bolzano: UNIBZ, shorturl.at/rSV47. Accessed 14 April 2023.

Sicher, E. (2022), 'EATING SCOBY A material-driven approach for symbiotic nutrition and glocal resilience', MA thesis, Bozen-Bolzano: UNIBZ, [unpublished].

Sterling, B., (2012). Bruce Sterling Explains the Intriguing New Concept of Design Fiction (Interview by Torie Bosch). Slate. Available at: http://www.slate.com/blogs/future_tense/2012/03/02/bruce_sterling_on_design_fictions_.html [Accessed

Villarreal-Soto, S. A., Beaufort, S., Bouajila, J., Souchard, J. P., & Taillandier, P. (2018). Understanding kombucha tea fermentation: a review. Journal of food science, 83(3), pp. 580-588.

Vitas, J., Popović, L., Cakarevic, J., Malbaša, R., Vukmanović, S. (2020) In vitro assessment of bioaccessibility of the antioxidant activity of kombucha beverages after gastric and intestinal digestion. Food and Feed Research, 47(1), pp. 33-42

Wensveen, S., & Matthews, B. (2014). Prototypes and prototyping in design research. In The routledge companion to design research (pp. 262-276). Routledge.

Wood, J. (2011). Languaging change from within; can we metadesign biodiversity?. Journal of Science and Innovation, 1(4), 27-31.

Zhou, Z., Brück, V., & Holzbach, M. (2022). A material-centric approach in non-anthropocentric design.

Emma Sicher
Emma Sicher is a transdisciplinary designer who investigates materials and foods made with microorganisms. Her education took place at the Faculty of Design and Art in Bozen/Bolzano, where she carried out research on SCOBY (Symbiotic Culture of Bacteria and Yeasts) during her BA and as a research assistant at the Design F(r)iction Lab. Projects she worked on have been exhibited at the Vitra

Design Museum, V&A Dundee, maat, and the ADI Design Museum. Recently she collaborated with the Laimburg Research Centre in South Tyrol by initiating a project on edible mycelium (Tempeh) and its local eco-social potential. With a focus on materiality, the semiotics of food, and system dynamics Sicher investigates how microorganisms can contribute to local resilience, themes she also elaborated on in the TEDx Bolzano 2023 edition. She is currently a PhD candidate at the HfG Offenbach and affiliated as a research assistant with the Matters of Activity Cluster of Excellence at the Humboldt University of Berlin. By focusing on human-plant-microbe relationships by interweaving design, microbiology, and cultural anthropology she is elaborating on the concept of Multispecies Matter as a holistic strategy for local and global resilience.

Seçil Uğur Yavuz
Seçil Uğur Yavuz is an associate professor at the Faculty of Design and Art, Free University of Bozen-Bolzano. She completed a Ph.D. in design at Politecnico di Milano and has a background in industrial design and product, service, system design. Her research spans the analogue and digital worlds to create tangible and embodied interactions, alternative modes of production and new types of hybrid materials (e.g. e-textiles). Through participatory design and co-design methods, her research takes place in contexts such as Fablab, makerspaces, schools and museums, engaging with children, makers and crafters.

Nitzan Cohen
After graduating from the Design Academy Eindhoven and working with Konstantin Grcic for several years, Cohen established his own design practice before turning to academia and design research. Cohen held the Chair for Industrial and System Design at HBK Saarbrücken and was an adjunct Professor at the Master for Space & Communication at the HEAD, Geneva. Cohen is currently a professor of product design and the Dean of the Faculty of Design and Art, at the Free University of Bozen-Bolzano. He founded the 'Design Friction Lab', a multidisciplinary Research Lab and Design Studio at the intersection of science and the industry, of reality, innovation, and vision. Looking for innovative sustainable solutions for an industrial and societal transformation. The Lab currently develops projects focusing on crafted products, electronics, and DIY culture, distributed manufacturing and open-source production, nano-electronics and biodegradable sensors, growing materials, alternative materials, and the development of circular design and production technologies. Cohen won several international design awards and his work is part of the most renowned design collections worldwide.

Designing Sustainable and Affordable Smart Home Solutions: The Role of Prototyping

Spadoni, Elena, Politecnico di Milano, Italy
Carulli, Marina, Politecnico di Milano, Italy
Barone, Chiara, Politecnico di Milano, Italy
Bordegoni, Monica, Politecnico di Milano, Italy

Abstract
This paper explores the use of prototypes in the design process of smart home systems, specifically focusing on a case study of a system called ModulAR. ModulAR is a system that uses Augmented Reality and the Internet of Things, to intuitively control aftermarket appliances that are designed to retrofit existing home devices. The goal of the system is to provide a sustainable and affordable way for people to improve their living spaces by giving them the ability to design and customize their home interfaces, rather than relying on pre-set options from proprietary providers. This allows for a greater degree of personalization. While smart home technology has the potential to greatly benefit consumers in terms of energy management, security and comfort, there are still several technical barriers and usability issues that need to be addressed in order for it to become more widely adopted. These barriers include interoperability, reliability, and security, as well as issues related to the configuration and "domestication" of the new interfaces. By using virtual and physical prototyping, it is possible to create new devices for modernizing older appliances and evaluate these ideas in a tangible and realistic way. By using prototypes to simulate real-world conditions, it is possible to gather valuable feedback on issues such as functionality, usability, and user experience. This feedback can then be used to make adjustments to the design in an iterative process, and to gather data on how users interact with the prototype and how changes to the design affect usability, User eXperience, and other factors.

Virtual and Physical Prototyping; Smart Home; User eXperience; Augmented Reality; Digital Twins

While Smart Home's positive impact on consumptions management, security and overall comfort already appeals to consumers, there are still several technical barriers – namely interoperability, reliability, and security – and usability frictions – as reliability, configuration and "domestication" of the new interfaces- that still prevent their diffusion.

Such problems will ideally be completely overcome with the horizontal integration of different industries delivering such services (De Silva et al., 2012) and a user-centered development of suited interfaces that support users in the processes of uncovering new spatial interaction logics. In the meantime, gradual efforts toward households' *smartification* mainly rely on Smart Home Controllers and smart devices that use Internet of Things (IoT) (Zhang et al., 2009) to connect and communicate with each other, allowing for remote control and automation of various household functions. These controllers and devices often include sensors, actuators, and a means of connecting to the internet, such as Wi-Fi or Bluetooth, that enables them to be controlled and monitored remotely using smartphones or tablets. Nevertheless, many household devices and appliances already in use cannot be easily integrated into a smart grid. Such frictions will ultimately be solved by disposing of such “old products” and replacing them with “new” ones, which is not a sustainable option.

Consequently, it would be intriguing to explore options for updating older devices, allowing for modernization of the home in an environmental-friendly manner. Using both virtual and physical prototyping would enable us to create new devices for modernizing older appliances and evaluate our ideas in a tangible and realistic way.

Prototypes can simulate real-world conditions and provide valuable feedback on issues such as functionality, usability, and User eXperience. Prototypes can be used to explore the use of technologies, including sensors and actuators, and also manufacturing processes.

By creating a virtual and physical prototype of the new device, we can get feedback from users on how it functions, how it feels, and if it meets the initially identified needs. This feedback can then be used to make adjustments to the design in an iterative process.

The prototypes can also be used in controlled experiments to test different design variables. This allows us to gather data on how users interact with the prototype and how changes to the design affect usability, User eXperience, and other factors. These data can then be used to inform the design process and to make evidence-based decisions.

This paper describes a case study concerning the role of prototypes in the design process of smart systems. In particular, the case study concerns the design process of ModulAR, a system that uses Augmented Reality and MQTT – the ISO standard messaging protocol for the Internet of Things - to intuitively control aftermarket appliances designed to retrofit home devices. Instead of buying new smart devices, users will be able to attach to their “old” appliances a cloud-connected motor with an add-on mechanism matching the physical interface. Finally, through an App, they can create automation to allow controlling the interface from afar.

The product is designed to appeal to a target audience looking for sustainable and affordable ways to improve their lived spaces. This means giving people the ability to design and customize their home interfaces, rather than relying on pre-set options from proprietary providers. This allows for a greater degree of personalization.

State of the art

Currently, the Internet of Things (IoT) is experiencing rapid growth, with increasingly complex systems of connected sensors and an increase in devices that are designed with software and services that cater to customer needs (Patel et al., 2017). Typically, a smart device is operated and managed through a dedicated application that can be accessed from a smartphone, which allows for remote control and data collection. While this type of offer may be sufficient for people who only have a few smart devices and use them independently, it prevents users from creating automation between devices from different vendors or limits them to pre-set rules for devices that can communicate with each other (El-Moursy et al, 2022). The presence of a broad variety of proprietary communication protocols and services is also creating friction at the user experience level (Heun, 2017). The current landscape of interactions proposed by various developers does not yet offer intuitive ways to translate logical concepts into physical actions among objects. To create meaningful connections within their living spaces, current user interfaces and interaction methods must be significantly redesigned.

Currently, while IoT systems are intriguing, they have significant limitations in their practical use. For people to fully experience the benefits of a connected home, technology and market policies need to advance enough to allow for horizontal protocols to coordinate products from multiple brands. In the meantime, smart objects are creating new demands for convenience but are causing older, non-connected appliances to become obsolete more quickly.

At present, people wishing for automation in their lived spaces have two options. The first and more complete solution is the professional installation. It is achieved by picking a service provider that will deliver a coordinated solution, provide the instalment by a professional and hand over to the customer the final interface from which they can control all the connected devices. Nevertheless, such a solution, while convenient can be costly and works by substituting and integrating new smart products in its household and not updating the old ones already in people's houses.

The second, most popular option is to purchase a smart home hub, such as the Aeotec SmartThings Hub, Google Nest Hub, Amazon Alexa, or Apple's home, and gradually integrating compatible devices either as new products or smart plugs to upgrade older appliances. The benefits of the Do-It-Yourself (DIY) approach are primarily flexibility and cost-effectiveness: users can gradually expand their smart device network by purchasing smart products and connecting them to their Hub, while also becoming familiar with the new logic of these systems. However, this approach has its limitations: users are restricted by the compatibility provided by their chosen Hub and may not be able to connect all devices, particularly those with more complex physical interfaces, such as buttons, knobs, and levers.

Regarding the User eXperience of connected systems, they typically use traditional, 2D interfaces with lists, cards, icons, and interactive elements to help users understand the connections they are creating among different products. Differently from more common solutions, the Reality Editor open project by MIT aims to create new interfaces using Augmented Reality (AR) technology, allowing users to envision and control smart objects in the physical world through an App (http://realityeditor.org/). Actually, AR and IoT devices are becoming increasingly integrated as technology advances (Lacoche et al., 2019). AR is a technology that overcomes digital information, such as images or text, onto a user's view of the real world. IoT devices, on the other hand, are physical devices that are connected to the internet and can collect and transmit data. IoT devices can be used to gather data from the environment and then send it to an AR application. This data can then be used to augment the user's view of the real world with information such as temperature, humidity, or air quality.

One example of how AR and IoT devices can be integrated is in the field of industrial maintenance. IoT devices can be used to gather data on the condition of equipment, and an AR application can overlay that data onto a user's view of the equipment, providing them with a visual representation of the equipment's condition. This can help maintenance workers quickly identify potential issues and make repairs more efficiently (Palmarini et al., 2018).

Overall, AR and IoT devices can be integrated to provide users with a more immersive and informative experience by overlaying digital information onto the real world. As technology continues to advance, we can expect to see more integration of AR and IoT in various fields.

Prototypes are an important part of the design process for IoT devices. Specifically, according to the User-Centered Design approach (Abras et al., 2004; Norman, 1986), prototypes can be used to evaluate several aspects of design solutions, such as the usability of the User Interface, and to gather feedback from users, and iterate on the design based on that feedback. Similarly, Agile development methodologies (Boehm, 2004) mainly used in the software development area, emphasise rapid iteration and testing, which is facilitated by the use of prototypes. In addition, due to the intrinsic complexity of IoT devices, testing and iterating on the design before committing to a final product is increasingly important. Several IoT prototyping approaches and tools have been proposed and reported in literature (Pramudianto et al., 2014; Mazzei et al., 2016; Chernyshev et al., 2018).

However, prototyping systems composed of AR applications and IoT devices can be a complex process, as it involves the integration of multiple technologies and the coordination of hardware, software, and network connectivity. Nevertheless, there are several tools and techniques that can be used to streamline the process.

As first tool, there are rapid prototyping boards, which allow for the rapid development and testing of electronic circuits and devices. They are typically composed of a printed circuit board (PCB) with pre-installed components such as microprocessors, sensors, and connectors. These boards, such as Arduino (https://www.arduino.cc/) and Raspberry Pi (https://www.raspberrypi.com/), are designed to provide a flexible, customisable and programmable platform to simplify the development process and quickly test different configurations and ideas. This can help identify any potential technical challenges or limitations early in the development process, saving time and resources in the long run.

For the AR component, Unity (unity.com) is a well-known development platform for games, which is nowadays used to develop AR and VR interactive applications for many other sectors, including design, engineering, manufacturing, and many others. In particular, it can be used to create interactive AR experiences to display data gathered by IoT devices.

For network connectivity, several platforms such as AWS IoT, Google Cloud IoT, and Microsoft Azure IoT can be used to prototype the communication between the IoT devices and the AR applications. These platforms provide tools for connecting, managing and monitoring IoT devices, and also support services for data analysis and visualization.

Main idea

Prototyping can be a useful tool for designing smart objects. A prototype is intended as a preliminary model – virtual or physical - of a smart object that can be used to test and evaluate different design concepts and features. Prototyping allows stakeholders, including designers, engineers, customers, and users, to visualize how the smart object will work in the real world, which can help identify any issues or opportunities for improvement. By building a physical representation of an idea, a prototype enables testing and experimentation in a tangible form, potentially leading to new insights, understanding, and the creation of theoretical knowledge.

Beaudouin-Lafon & Mackay state that prototypes can support *creativity*, helping to capture and generate ideas, encourage *communication*, facilitating stakeholders in discuss options and interact with each other, and permitting early evaluation through testing sessions (Beaudouin-Lafon & Mackay, 2009).

Usually, the IoT systems present complex configurations made by objects equipped with sensors, actuators and communicating with each other. In this case, the design and development of a prototype can be useful to test the initial system configuration and to understand the limits and possible improvements, particularly taking in account general aspects related to the front-end user interface, the back-end software, the hardware device and the connectivity between the different objects.

The paper describes an experimental design project – named ModulAR - focused on developing a prototype of a system to "make non-smart and non-connected devices smart and connected", which will then be used in user testing.

The system's design uses a prototype-based method, incorporating feedback from prototype testing to inform the design of its mechanisms (Fig. 1). Two kinds of tests have been performed: the developers have performed preliminary functional tests to find out and fix the major functional issues, and users have been asked to perform usability and user experience tests to evaluate typical user Interface-related aspects such as learnability, satisfaction, and task completion. The testing phase, performed by adopting the developed prototype is valuable for providing feedback on adjustments and on changes to perform on the final product. The design system process is conceived as an iterative process in which it is possible to meliorate and test the designed solution many times.

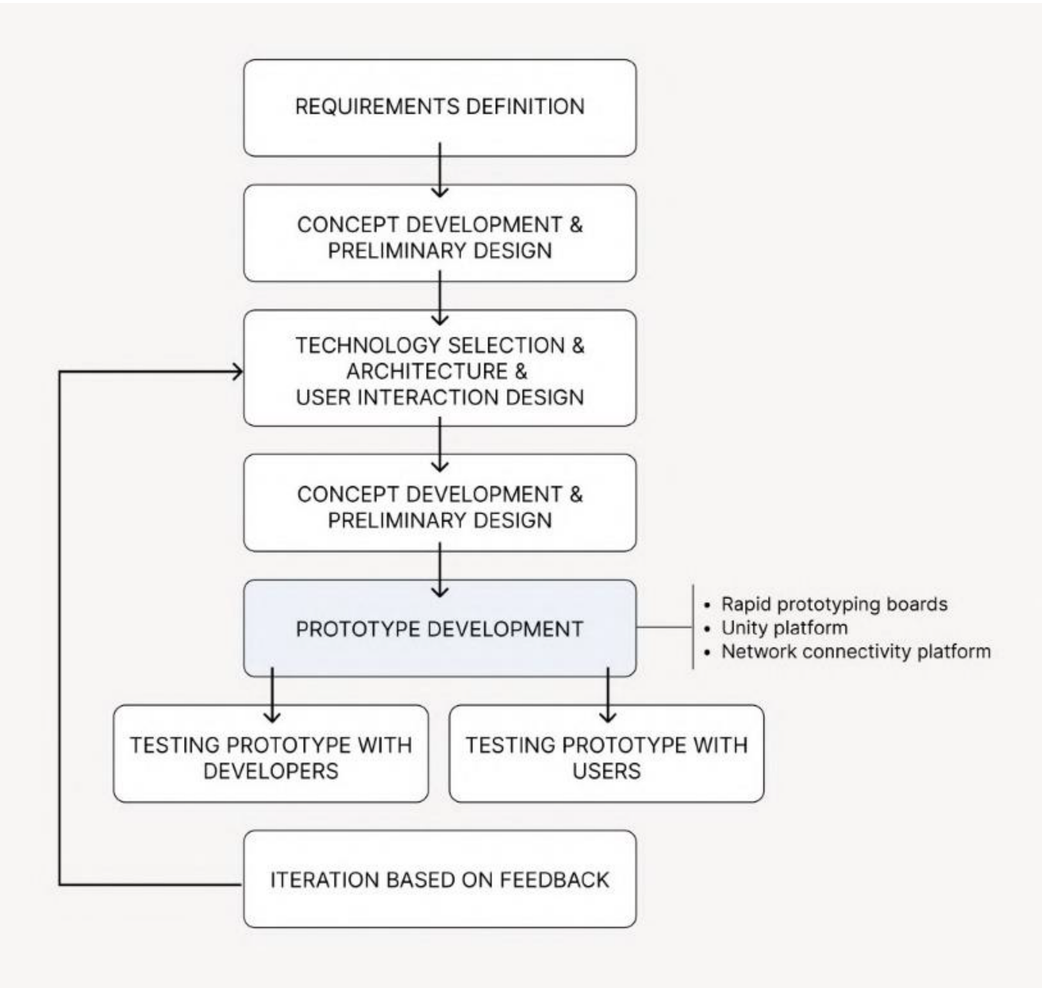


Figure 1. Flow diagram of the prototyping-driven design of the ModulAR system

ModulAR can be viewed as a system that improves the relationship people have with their objects by making them "smart" without requiring their replacement. It consists of a series of mechanisms incorporating IoT technologies that can be connected to traditional product interfaces such as buttons, knobs, and switches to enable remote control (Fig. 2). For example, ModulAR can be useful to switch on/off the lights at home, to control the domestic appliances or to turn on/off the volume of a speaker. This provides users with the opportunity to upgrade their older devices and experiment with creating automation to support their daily routines. Moreover, a smartphone application allows the user to easily control and set the mechanisms remotely.

Additionally, to provide more intuitive support for users to connect logical ideas with physical objects, the system incorporates Augmented Reality-based elements, which are presented as Graphical User Interface (GUI) screen elements overlaid on real objects and as 3D elements which help users envision new solutions and actively guide them through configuration processes. Other than the focus on the tangible mechanisms, particular care was taken also in design of the GUI and the Augmented Reality contents, taking advantage of the flexibility of the former and the physicality of the latter technology. The main functional elements of the ModulAR system are the following:

- *modular elements* to hack the physical objects interfaces;
- *digital twin* for each mechanism to allow easy visualisation and configuration of the physical mechanisms;
- *interconnectivity* among mechanisms to allow the creation of automations.

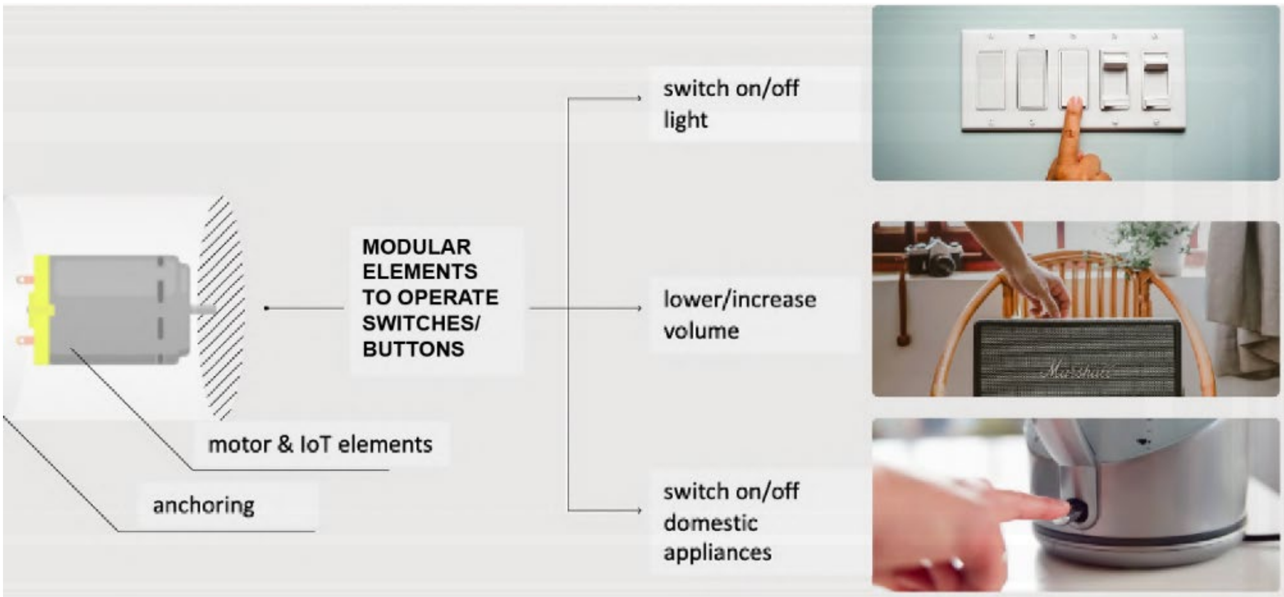


Figure 2. Mechanisms connected to traditional product interfaces (switch, buttons, and knobs) to enable remote control.

Design and development

The following details the creation of the ModulAR system to fulfil the three main functions listed above. Three disciplines were involved in the development: industrial design for the design and manufacturing of the modular elements, interaction design and user experience design for the design of the smartphone application, the AR interaction and interconnectivity among the mechanisms.

Functional element #1: Modular elements to hack the physical interfaces

To create a product capable of interacting with a wide range of physical interfaces, the authors focused on the basic actions that humans perform on physical objects - pushing, pulling, turning, and sliding - and attempted to replicate them using a motor and additional mechanisms. Mapping the main interactions between human and domestic objects was fundamental to identify a design pattern that could be adapted to many physical interfaces. Indeed, even if some systems that allow to control physical interfaces already exist on the market (https://www.kickstarter.com/projects/adaprox/fingerbot-plus) sometimes they tend not to be versatile and applicable to different physical objects configurations. In order to give users the ability to customize the ModulAR system and extend it to a wide number of objects, it has been decided to design a modular system composed of a cubic base unit equipped with a motor and six interchangeable modules (Fig. 3). The six modules consist of a smooth wheel, a single lever, a double lever, a pair of gear wheels, a perforated plate and a plate equipped with a knob.

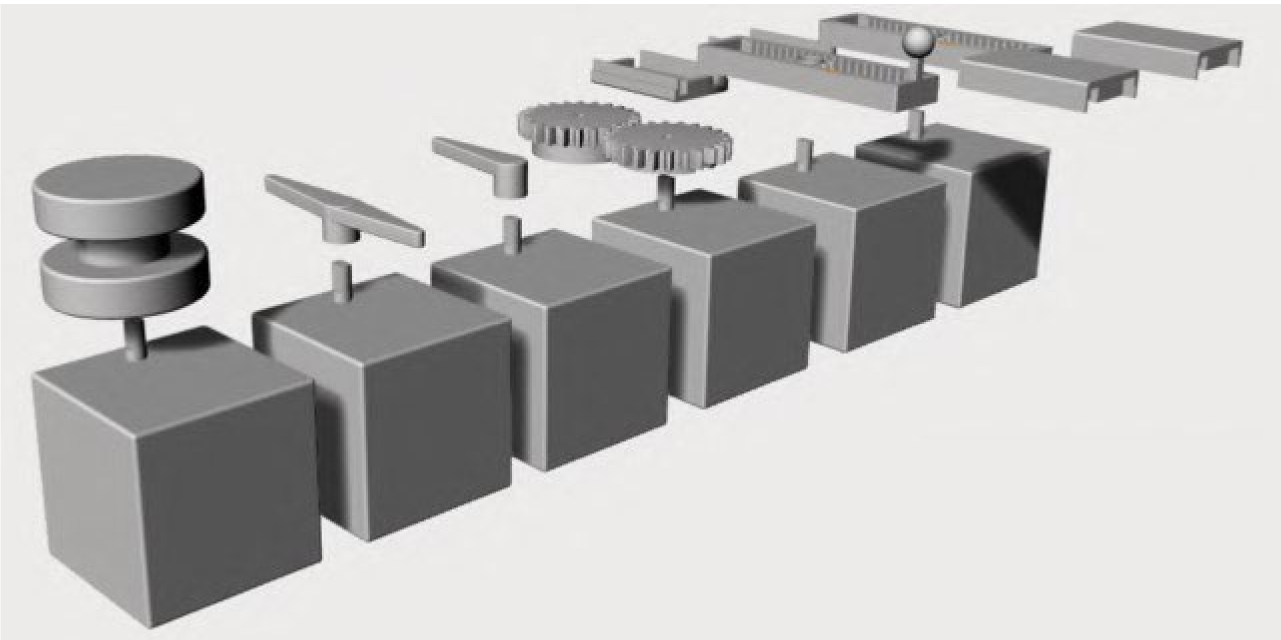


Figure 3. 3D model of the modular system composed of a base unit equipped with a motor and six interchangeable mechanisms.

A low-fidelity physical prototype of the modules and the base unit have been developed to evaluate their shapes and modularity, and to test the usability. The modules have been used to hack a lamp and a speaker as shown in Fig. 4. Rhinoceros (www.rhino3d.com), a 3D modeling software, have been used to design the digital models, which have been then 3D printed, using the Fused Filament Fabrication technology.

Figure 4. Low-fidelity physical prototype of the system created with the base unit and different modules: a) single pivoting lever, b) belt created by using the smooth wheel, c) pair of gear wheels.

The 3D printed modules have been then connected to the base unit, that contains parts of the circuit and allows the functioning of the system (Fig. 4). The final version of the circuit has been achieved after several iterations and includes an ESP8266 board powered via USB, a stepper motor and its driver circuit which is powered by 5V. The communication between the board and the motor was facilitated by a 4 Channel IIC I2C Logic Level Converter BiDirectional Module 5V to 3.3V and the power supplied to the motor was regulated by a transformer that converted 9V to 5V.

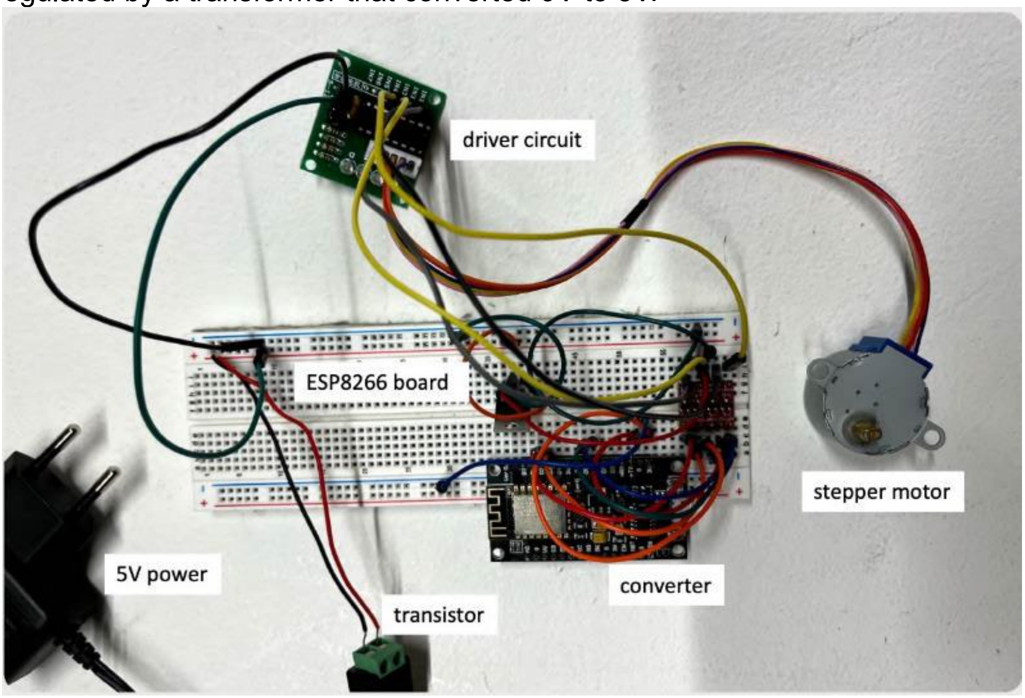


Figure 5. Circuit to operate the base unit.

The system was completed by creating a coordinated image, packaging, and manual of instructions to simulate the product for the market (Fig. 6). The branding of the system consists of patterns that have been designed to be used also as targets for activating the Augmented Reality (AR) contents. The patterns cover the body of the basic module, where contextual information about the elements movements is displayed in AR, and are also placed on the instruction manual, where AR animations inform users about the system concept.

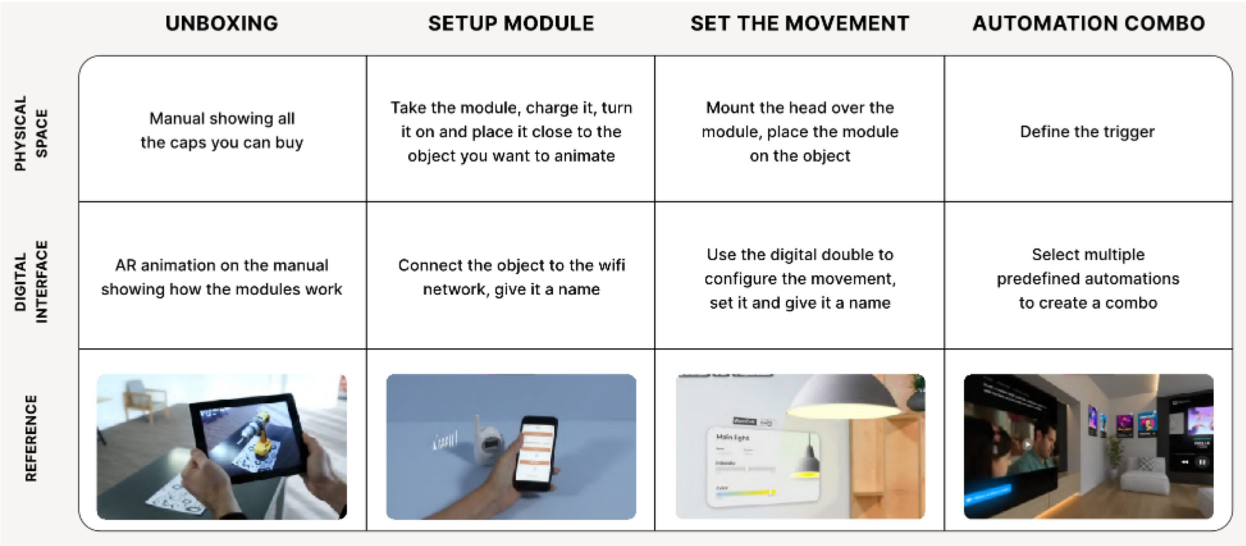
Figure 6. Image of the packaging and manual of instructions of the system.

Functional element #2: Digital Twins for each mechanism to simplify elements' configuration.

To help users imagine the possibilities offered by ModulAR, guide them through the configuration of the module movements and help them define the automations, it was decided that Graphical User Interfaces (GUI) were not fully satisfactory, and to opt for the integration of AR technology. In fact, while GUIs are very suitable for guiding users through the different functions provided by the system thanks to interactive menus and animated instructions, AR is very helpful for providing a layer of contextual information overlaid on physical objects and visualizing the connection logics between the states of intelligent objects.

Therefore, it was designed and implemented a smartphone application proposing a set of functions, some activated through a GUI and some others through AR technology. Each of the six modular elements mentioned above presents an associated digital twin, accessible through the smartphone application. The digital twins consist of the 3D model of each element connected with IoT, that the user can visualize in Augmented Reality. This aspect allows to easily monitor and control each physical element remotely, acting directly on the digital twin by using both the GUI and AR.

The design of the app was based on the analysis of a user journey (Fig. 7).



***Graph 2** - ModulAR's expected user journey.*

Figure 7. ModulAR system user journey.

The app is designed with a customised information architecture, allowing the user to access all the functions from a main page. The main page is divided in two sections, the *Single Control* and the *Automations*, that allow us to control both the single modules and the interconnected elements. Moreover, at the centre of the main page, a floating button allows us to open the smartphone camera, to easily scan the target and activate the AR content.

As mentioned, the AR targets are both on the manual of functions and on the base unit. The AR content have been designed mixing autonomous animations, which help the user imagine the use of the product, and interactive functions, to better explore and verify the use of the system.
The main AR functions implemented are the following:

- *AR manual:* it is activated by framing the physical manual of instructions and supports the user in selecting the most appropriate mechanism, by previewing the supported movements.
- *AR movement setup*: it is activated by framing each physical mechanism and allows users to setup custom range of movements for the specific mechanism.
- *AR automation creator:* it is activated by framing physical mechanisms and allows users to connects multiple mechanisms and set triggers to create custom automations.

The development has been carried out mainly using open-source software. The GUI interfaces have been developed using the collaborative interface design tool Figma (www.figma.com). The Figma to Unity Importer plugin has been used to easily transfer UI layouts to Unity (www.unity.com), a cross-platform game engine that was used to create 2D and 3D interactive experiences.
The AR Interactions were built using Vuforia, an Augmented Reality software development kit for mobile devices that uses computer vision technology to recognize and track planar images in real time. The AR space was designed to be elicited by target images. It was then populated with 3D elements separately modelled on Rhinoceros (www.rhino3d.com), and GUI elements provided by the Lean GUI library (www.leangui.com), a collection of components that extend the Unity GUI system. To achieve formal coherence with the files imported from Figma the Unity-UI-Rounded-Corner was used as well.

Function #3: Interconnectivity among the mechanisms to allow automations

The last requirement to implement was the communication between the mechanisms. The modules have the following characteristics:

- have communication range of a few meter (to work freely at any household);
- maintain two-way responsive communication;
- work on a board programmable with Arduino IDE;
- integrate with Unity;
- be low power.

To implement all these characteristics, it was decided to use MQTT (the ISO standard messaging protocol for the Internet of Things) for communication, along with an ESP8266 card.
The chosen communication protocol had a very small code footprint, making it ideal for use on resource-constrained devices such as the ESP8266 card. In addition, it was used a publish/subscribe model which makes it easy to implement multiple ESP8266 modules communicating with each other at an unnoticeable delay.
At first, a public MQTT broker was used for communication (Fig. 8). However, due to its unreliability caused by power outages, user overload and lack of update, it was decided to switch to a self-hosted version. It was set up a dedicated Linux server, running the Mosquitto broker, to make a private and secure connection between the modules. It was necessary to bridge the communication between the app and individual ESP8266.

Figure 8. Code and interface ensuring the communication with the MQTT broker.

User Experience

The user experience has been designed to be intuitive and to guide the user in each step, during the use of the product. After unboxing the modular elements, the user can read the instruction manual to understand the basic functioning of the product. Moreover, the user can also use the smartphone App to scan the AR target presented on the manual and start the creation of each digital twin, through the use of AR. During this onboarding phase, it is also possible to see the digital twin and manipulate it (Fig. 9).

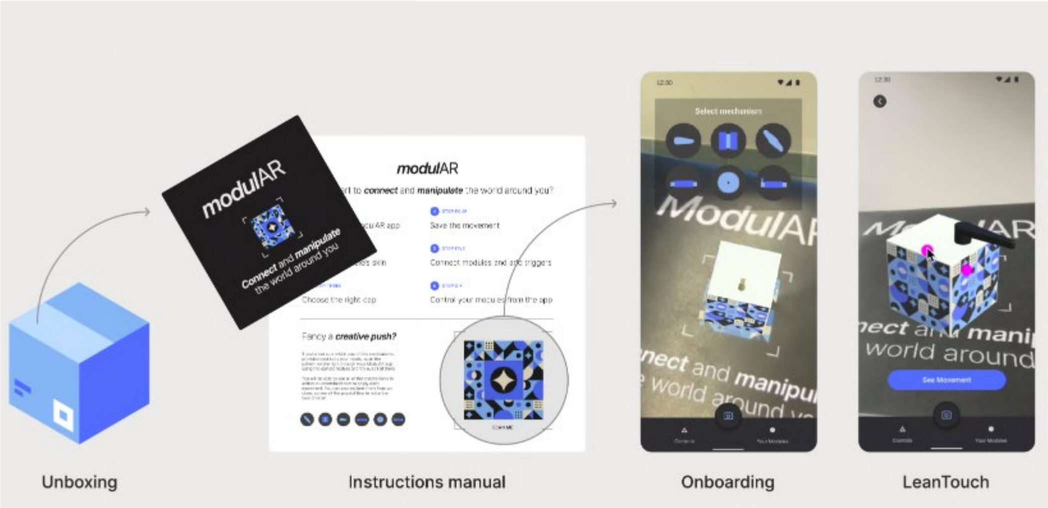


Figure 9. Unboxing the product and creating the digital twin.

Then, the user can attach the corresponding physical module to the object interface that he/she wants to control. The App allows the configuration of each module by assigning an on/off value and a maximum rotation degree to it, through the use of AR.
As shown in Fig. 10, in the *Single control* section of the application, it is possible to control each module, by assigning an action and a name to it. It is also possible to change the value of each module by using simple GUI elements, such as one or two buttons, a toggle or a slider. When the value is set to on, the motor included in the base unit is activated and the traditional object interface is triggered.

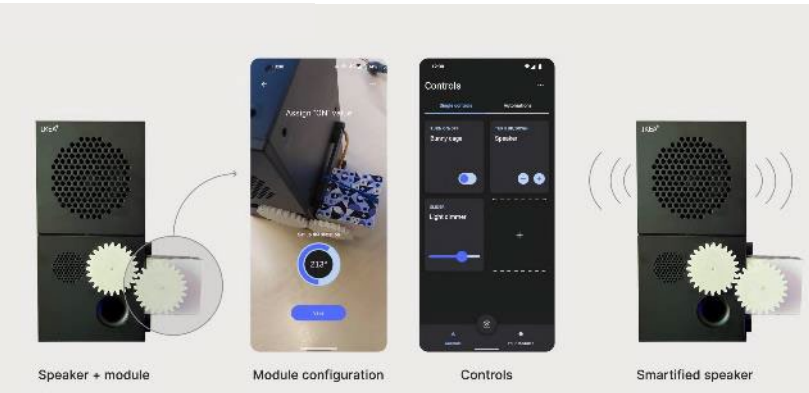


Figure 10. Use and configuration of each module.

In addition, from the App it is also possible to create interconnected devices, creating automated configurations. This is done by connecting the digital twins together and by programming actions that can be performed simultaneously by the linked modules.

As shown in Fig. 11, the automation setup is made by scanning the modules and visualizing and controlling the digital twins in AR. During this process, on the top of each module, an AR interface gives information to the user on the state of each control and on the created automations. In addition, the *Automations* section of the app allows us to check the automations already added, modify and add or remove them.

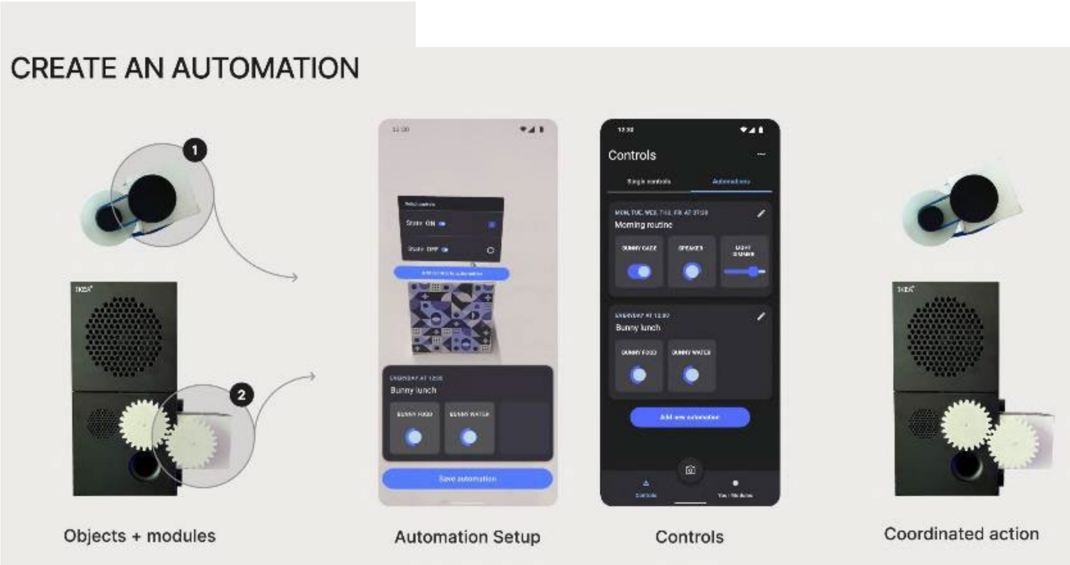


Figure 11. Creation and configuration of system automations.

Testing sessions with users

Some preliminary tests were carried out with users to understand their confidence while shifting from 2D traditional interfaces to AR sections of the application. Firstly, the team asked four users to respond to an A/B test focusing on the interaction necessary to configure the modules.
Users reported that the rounded slider was more intuitive than the straight one as it was reproducing the movement of the motor. Also, they did not think that having numeric feedback about the degree to which the motor was moving was necessary.
Tests were also carried out on the onboarding section of the App, where users can interact with the 3D models of the modules by rotating and moving them. Some users reported that they would have preferred to have some guidance, as it was an unusual interaction. The team therefore added two informational pages, to help users familiarize with the gestures available on the App.
Finally, an initial prototype of the panel appearing on the target during the automation configuration process, featured it appearing on the side of the module. This forced users to turn the orientation of the phone, causing some friction. To optimize the interaction, panels were moved on top and on the bottom of the module so that they fit in the vertical ratio of a mobile device.

Figure 12. User's tests on the virtual and physical prototype.

Discussion and Conclusion

Prototyping methods can be useful tools during the design process for several reasons. In fact, the creation of virtual or physical prototypes allows for verifying aspects related to functionality and interaction, gathering direct feedback from users, and consequently exploring and validating innovative solutions quickly. This offers the possibility for the stakeholder, and especially for designers and engineers, to iterate some phases of the design process based on the obtained feedback with the aim of reaching an insightful solution.

The paper suggests using virtual and physical prototyping to explore the use of sensors and actuators in designing devices for smart homes. It also proposes gathering data on user interactions and design variables. The paper starts by discussing the potential benefits of smart homes and the barriers to their widespread adoption, such as interoperability, reliability, and usability issues. It suggests that horizontal integration of different industries and user-centered development of interfaces can help overcome these barriers. The paper also highlights the need for sustainable solutions that allow for the modernization of older devices instead of replacing them with new ones. It presents a prototype of a device developed for modernizing old smart home devices called ModulAR system.

ModulAR system uses Augmented Reality and MQTT to control aftermarket appliances designed to retrofit older devices, which allows for customization and personalization. The target audience for this product is people looking for affordable and sustainable ways to improve their living spaces. The result of the iterations on the different prototypes resulted in a product that presents a high degree of usability and appeals to users for its novelty. Users report to be intrigued by the way the different layers of virtual and physical intertwine and the latest tests report smooth transitions between the different stages. Users also thought it was a fun product that they would gladly try out with the devices they have at home. During the debriefing of the tests, some people also shared some ideas for how the modules could be used, showing that the DIY aptitude required by the product is elicited by the exposure to the introductory animations. ModulAR is a product with the potential to introduce people to spatial logics of interconnection among objects, giving them a taste of how a fully connected home will be.

The research presented in the paper shows that prototypes can be developed starting from existing old devices, aiming at filling only the issues found and focusing just on aspects to be verified with end users related, for example, to the usability of the proposed solution. In this case, prototypes do not represent the final product entirely but reflect hybrid solutions that can be combined with existing objects just to be adopted in the testing phase. This aspect proves to be very useful, especially for the design of IoT systems, which usually present complex configurations, and in which prototyping methods can offer the opportunity to update old existing devices by adding functional and interactive components.

Testing new interactive IoT configurations with end users can be useful for understanding the limits and possible improvements of existing objects in relation to design aspects, such as usability, and implementation aspects, such as hardware and software configuration. The use of prototypes to understand how old objects can be modernized, integrating technological components, and avoiding completely replacing objects with new solutions, offers an interesting starting point also in relation to the sustainability issue.

Acknowledgements

The authors would like to thank Giulia D’Aleo, Claudia Mazzuca and Jan Ostrowka, students of the Virtual and Physical Prototyping course, School of Design, Academic Year 2020/2021 for their valuable contribution to the research.

References

Abras, C., Maloney-Krichmar, D., Preece, J. (2004). User-Centered Design, in Bainbridge, W. Encyclopedia of Human-Computer Interaction. Thousand Oaks: Sage Publications

Beaudouin-Lafon, M., Mackay, W. E. (2009). Prototyping tools and techniques. In HumanComputer Interaction, pp. 137-160. CRC Press.

Boehm, B. (2004). A Survey of Agile Development Methodologies.

Chernyshev, M., Baig, Z., Bello O., Zeadally S. (2018). Internet of Things (IoT): Research, Simulators, and Testbeds, in IEEE Internet of Things Journal, vol. 5, no. 3, pp. 1637-1647

De Silva, L.C., Morikawa, C., Petra, I.M. (2012). State of the art of smart homes, Engineering Applications of Artificial Intelligence, 25 (7), pp. 1313-1321

El-Moursy, A.A., Sibai, F.N., Rehman, J., Gouda, O.M., Gaber, A.T., Khedr, A.M. (2022). Home Automation Using Augmented Reality (HAAR). Wireless Pers Commun 124, 1525–1555

Heun, V.M.J. (2017). The Reality Editor: An Open and Universal Tool for Understanding and Controlling the Physical World, https://dspace.mit.edu/ handle/1721.1/11407/

Lacoche, J., Le Chénéchal, M., Villain, E., Foulonneau, A. (2019). Model and Tools for Integrating IoT into Mixed Reality Environments: Towards a Virtual-Real Seamless Continuum, 2019 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments

Mazzei, D., Baldi, G., Montelisciani G., Fantoni, G. (2016). A full stack for quick prototyping of IoT solutions, Cloudification of the Internet of Things (CIoT), Paris, France, pp. 1-5

Norman, D.A. (1986). User-Centered System Design: New Perspectives on HumanComputer Interaction

Palmarini, R., Erkoyuncu, J.A., Roy, R., Torabmostaedi, H. (2018). A systematic review of augmented reality applications in maintenance, Robotics and Computer-Integrated Manufacturing, Volume 49, pp. 215-228

Patel, M., Shangkuan, J., Thomas, C. (2017). What's new with the internet of things? https:// www.mckinsey.com/industries/semiconductors/ our-insights/whats-new-with-the-internet-of-things

Pramudianto, F., Kamienski, C. A., Souto, E., Borelli, F., Gomes, L. L., Sadok, D., & Jarke, M. (2014). IoT Link: An Internet of Things Prototyping Toolkit, IEEE 11th Intl Conf on Ubiquitous Intelligence and Computing and 2014 IEEE 11th Intl Conf on Autonomic and Trusted Computing and 2014 IEEE 14th Intl Conf on Scalable Computing and Communications and Its Associated Workshops, Bali, Indonesia, 2014, pp. 1-9

Zhang, B., Rau, P.L.P, Salvendy G. (2009). Design and evaluation of smart home user interface: effects of age, tasks and intelligence level, Behaviour & Information Technology, 28:3, 239-249

Elena Spadoni
Elena Spadoni is a s Ph.D. candidate in Design at Politecnico di Milano. Her research concerns mainly the Design process for the integration of Extended Reality technology in the Cultural Heritage field, but her scientific interest relays also on User Experience Design and Virtual Prototyping Technology. She previously graduated in Product Design as Bachelor's and in Digital and Interaction Design as Master of Science, at Politecnico. In the past years, she worked as a freelancer on different Design projects, mainly regarding UX/UI Design, she covered the role of assistant and tutor in some courses at Politecnico, and she conduted a one-year Research Fellowship at the Mechanical Engineering Department of Politecnico.

Marina Carulli
Marina Carulli is an Associate Professor at the Mechanical Engineering Department of Politecnico di Milano. She is a product designer and received a Ph.D. in Virtual Prototypes and Real Products from Politecnico di Milano in 2008. She has been Post-Doc fellow at the Department of Mechanical Engineering of Politecnico di Milano from 2008 to 2016. Her research interests include design methods, integration of tools for Virtual Prototyping within the product development process, Virtual Prototyping techniques for product design and for cultural purposes, olfactory technologies, Multisensory User Experience. She has co-authored more than 60 scientific papers published in proceedings of Scopus-indexed conferences (including ASME, IEEE conferences) and published in refereed scientific journals and has served on roughly twenty conference program committees.

Chiara Barone
Chiara Barone is a Marketing Officer with a M.sc degree in Communication for business, the media and complex organizations from the Catholic University of the Sacred Heart of Milan

Monica Bordegoni
Monica Bordegoni is full professor in the Department of Mechanical Engineering, School of Design of the Politecnico di Milano. Her research interests are in the areas of product design methods, virtual and physical prototyping, extended reality technologies, user experience design, and multisensory interaction. She has published around 300 peer-reviewed scientific papers in international journals and conference proceedings and has served on roughly fifty conference and workshop program committees. She is member of the Advisory Board of the Design Society. She has been the principal investigator of several funded research projects.

Track 5: Materials and Crafts

- How ecodesign requirements fuel the design process for yarn production and what challenges must be overcome from a spinning perspective

- Prototyping a novel visual computation framework for craft-led textile design

- Materials Libraries: designing the experiential knowledge transfer through prototyping

- New Textile Transmissions: Reviving traditional textile crafts through replication, unlearning and prototyping

- Shimmering Wood – Design “Thinging” in Material Development Process

How ecodesign requirements fuel the design process for yarn production and what challenges must be overcome from a spinning perspective

Brigitt Egloff, lecturer and applied design researcher at the Product & Textiles Research Group at Lucerne University of Applied Sciences and Arts

Abstract

Old or waste textiles are a modern phenomenon and a problem of highly industrialised societies. The linear economic model of the textile industry and our appetite for fast fashion has serious impacts on the environment, characterised by short use phases, low reuse and reparability, and low rates of fibre-to-fibre recycling. The European ecodesign requirements regulation establishes a framework for improving the environmental sustainability of products by 2026.[1]
This paper focuses on the spinning process using recycled fibres as a sub-sector of the circular economy and the specific hurdles arising from the ecodesign requirements for the design process.
With concrete, marketable prototypes, the complex challenges relating to the spinning sector are addressed using examples. The development of a prototypical poly-cotton recycled ring yarn from pre-consumer baker uniforms is shown: from materials sourcing to production and product application. This research project combines empirical, experimental approaches in cooperation with textile producers, including research on the framework conditions, regulations and standards which pose real challenges for spinning mills and designers when dealing with mechanically recycled fibres.

Prototype, recycling ring yarn, mechanical textile recycling, design, ecodesign requirements

Introduction

Textiles are the fourth largest consumer of primary raw materials and water, and the fifth largest emitter of greenhouse gases, after food production, housing and transport.[2] It is estimated that less than 1% of all textiles worldwide are recycled into new textiles.[3]
Given the complexity of the textile value chain and the significant challenges related to textile sustainability, the European Commission is developing a comprehensive strategy to address the environmental challenges.[4] The strategy's objectives include building a sustainable framework for

[1] COM, 2022, 142 final
[2] Cf. EUA-Briefing, 2019 in COM, 2020, 98 final
[3] Ellen McArthur Foundation, 2017, A new textiles economy
[4] Cf. COM, 2020, 98 final, COM, 2022, 142 final

the circular economy of suitable textile products and ensuring the use of secondary raw materials. The strategy also aims to promote the sorting, reuse and recycling of textiles.
With the emergence of circular practices that re-envision waste as a resource, end-of-life textiles are undergoing a shift in value as well as a resurgence.[5] As a result, a key field of action has opened up, particularly from a design and industry perspective. "*Recycling"* is defined as the return and introduction of used and waste textiles into the manufacturing process of consumer goods or the reuse of these materials.[6] It includes industrial textile waste in the form of fibres, yarns, fabric remnants, materials from production phases (post-industrial waste), unworn or unused textile products (pre-consumer-waste) and garments after use (post-consumer waste).[7]
In the 2020 Action Plan for the Circular Economy, it is said that textiles were urgently identified as an essential product value chain with great potential for transitioning to sustainable and circular production, consumption and business models[8]. By promoting reuse, repair as a means to extend the life of products, recycling of individual components, and textile recycling[9] (explicitly targeting fibre-to-fibre recycling), a change in the current situation can be brought about. The aim is to reduce the use of non-renewable resources and the environmental impact of production and consumption.[10]
Embedded in the traditional process chain that constitutes industrial textile recycling are the collection, sorting, processing and reselling of used textiles, as well as further processing in the rag industry, the production of tear fibres, and processing into insulation materials and recycled yarns.[11] To date, the individual processes have mostly been labour-, cost-, and energy-intensive. Precise sorting according to specific criteria (condition, typology, material, colour) forms the basis for quality in the subsequent process steps. The frequent use of material mixtures by industry, which is used due to their functional properties and price advantages, also poses a challenge for today's recycling technologies.[12] In the sense of a designed end-of-life, there is an urgent need for action in order to develop closed technological or biological cycles in alignment with adequate recycling or recovery processes. All of these challenges require systemic solutions in line with the European Green Deal,[13] which aims for sustainable, climate-neutral, energy- and resource-efficient, and nature-friendly growth based on a circular economy.
Some companies are now focusing on improving sustainability towards a circular economy in the textile sector although progress is somewhat slow. As such, design research can support these processes and drive them forward by developing laboratory-scale feasibility studies and exploratory experiments, while developing proof of concepts using prototypes. Moreover, such research can test feasibility in iterative processes and, in particular, make theory-based ecodesign practices both able to experienced and communicable. However, the methodological approach in this project involved a combination of process design and material- driven design[14] at a micro and macro level.[15]
Bearing this in mind, the present paper will examine the significant challenges that designers and spinning mills encounter when dealing with recycled fibres. A recycling yarn prototype will be used

[5] Stahel, 2016
[6] Sandin, 2018
[7] Sandvik and Stubbs, 2019
[8] COM, 2020, 98 final
[9] Cf. Ellen Mac Arthur Foundation, Circular economy systems diagram, 2019, www.ellenmacarthurfoundation.org, diagram based on Braungart and McDonough, Cradle to cradle principle
[10] Kazancoglu et al., 2020
[11] http://www.bvse.de/themen/geschichte-des-textilrecycling/der-weg-von-der-sammlung-zur-wiederverwendung.html, [Visited : 31.2.2022]
[12] Of particular concern here are the effects of the world's most widely used pulp polyester, which, according to the Textile Exchange 2021, accounted for around 57 million tonnes, or 52%, of total pulp production in 2020, see Textile Exchange 2021 at https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf, [Visited: 28.06.2022]
[13] COM, 2019, 640 final
[14] Karana 2015.
[15] Latour 2006.

to demonstrate the complexity of the interplay between external influencing factors — the future EU legal situation and the quality standards already in-force — and the internal, real challenges of the spinning process.

Conceptual framework

The answer to the above research question is based on the example case and yarn prototypes, which are part of the Texcircle research project based at the Lucerne University of Applied Sciences and Arts.[16] The project developed and examined the vision of a paradigmatic textile circular economy for used textiles. Based on real conditions, Texcircle optimises processes, while also designing and developing specific product cycles. Furthermore, it also examines significant product sustainability decisions concerning the design phase in circular processes.
As part of the research project, a “decision tree” tool has been developed in order to assist designers in making informed decisions about material resources, material combinations, and processing technologies along and beyond the entire life cycle of products. Since materials are treated, combined and joined in such a way that they are recyclable or biodegradable, from a design perspective, the tool also supports the spinning process and provides information by making tangible the dependencies and complexities of a given issue.[17]
In the study described here, the clear challenges for the yarn production sub-sector will be examined from the two internal perspectives of design and the spinning mill, and reflected upon, based on external influencing factors such as standards and the legal situation.

The starting point of this study includes the following:

1. Identifying three process phases relevant to spinning: the input phase (with raw material procurement), the spinning process (with a focus on material blends), and the output phase (with textile manufacturing and product development). These process phases represent several stakeholder groups within the textile value chain. The study of the ring yarn described here is based on interviews and observations from the yarn production process, which took place between February and August 2022. Further interviews with recyclers (input phase), weaving and knitting experts, and a sock and workwear manufacturer from the output phase (see Table 1), complement the data obtained from the spinning process.
2. The research project was about creating a reference to reality and creating these realities themselves. The making of realities in the prototyping of the spinning process took place within the framework of existing knowledge and a new legal situation, as well as based on technical knowledge and design criteria. In design, yarns were to be developed beyond logically continuing what is and was. Thus, the yarn experiment tested the hypothesis and the effectiveness of this hypothesis using product prototypes. The innovation goal for targeted yarn was: to achieve the finest possible yarn quality with maximum recycled material content for mixed fibre qualities. The yarn serves as a basis for discussing the individual stakeholders’ knowledge transfer within the process phases mentioned in the previous point.
3. Information from literature, regulations and standards is used throughout the process to explain why specific hurdles come about during the process of producing yarns from recycled fibres.[18] Implementing the European Commission’s ecodesign requirements (the Ecodesign

[16] Adler, 2022 Texcircle – circularity for textiles
[17] Adler, 2021, Design decision tool
[18] Eisenhardt, 1989

for Sustainable Product Regulation) is expected to significantly improve the environmental sustainability and recyclability of textile products.[19] Later in this paper, the empirical material and findings from the spinning process will be presented in tabular form and contrasted with the relevant contextual factors from literature. On the one hand, this approach confirms the reality but also pinpoints the gaps, as well as the research and action fields concerning targeted regulations and standards.

Methodology

The role of design is considered, for the purposes of this paper, as the clear starting point of recycling practices.[20] The focus is on developing a marketable prototype as a means of cooperation between research and production.
The qualitative research method and the explorative research approach chosen are central to this paper. As mentioned in the Conceptual Framework, they are conducted from two perspectives: a design one and a spinning one. The observations and analyses from the iterative series of experiments along with the interviews conducted with representatives from the different process phases made it not only possible to filter out the most relevant internal challenges in the spinning process, but also to formulate recommendations for both the design and the spinning processes. Responding to the research question, four interviews were conducted with recycling experts, two were performed with spinning experts, while another two interviews were held with fabric or product manufacturers. All interviewees were directly involved in the research project described above. The interview questions were designed in such a way that experiences and difficulties encountered when dealing with recycled fibres could uncover any knowledge gaps between the individual process phases. The exchange between the stakeholders could also lead to a better understanding of the requirements and needs.
The interviews with experts from the input, spinning and output phases were semi-structured and open-ended; they took the form of guided conversations rather than structured interviews. Interviews generally lasted between one and two hours, and were recorded and later transcribed. The subsequent analysis of the interviews was based on descriptive coding concerning the challenges faced by the given design and spinning experts in order to condense the relevant topics affecting these two perspectives.[21]
In the following, interviewed development partners are anonymised. Documents provided by them are not mentioned separately in the source appendix. The interviews have led to answering questions on process stability in the manufacturing process and among textile and product manufacturers in relation to the technical and aesthetic performance of the recycled yarn. The evaluation of the interviews from the tearing process resulted in factsheets with cumulative data on the target sizes for fibre lengths and blends, target sizes for the targeted yarns, process stability, fibre waste and spinning quantities.
Furthermore, laboratory tests of different tear fibres proved their suitability. The starting point of these tests was an analysis of the material composition, colour and processing types (knitted and woven) ten different types of tear fibres. From this, the spinning partner was able to define the maximum spin-out limit for post-consumer and pre-consumer recycled yarns, and derive

[19] COM, 2022, 142 final
[20] Hall, 2021
[21] Miles, Huberman, and Saldaña, 2014

recommendations for the preferred fibre blend of recycled fibres with virgin fibres. The criteria describing the quality of the tear fibres for the spinning process are a balanced proportion of short, medium and long fibres.[22] The data from the tear fibre and yarn tests were reviewed in order to get an overall understanding of yarns made from recycled fibres. In addition, the yarns were examined to ascertain their regularity, tensile strength, hairiness and nep content. In turn, the products made from recycled yarns were subjected to abrasion and pilling tests. The findings from a spinning perspective were published in Melliand Textilberichte.[23] It should be noted that the case described is distinguished from yarns made from virgin fibre material.
The findings from the input phase, the spinning process and the output phase are described in the following chapters.

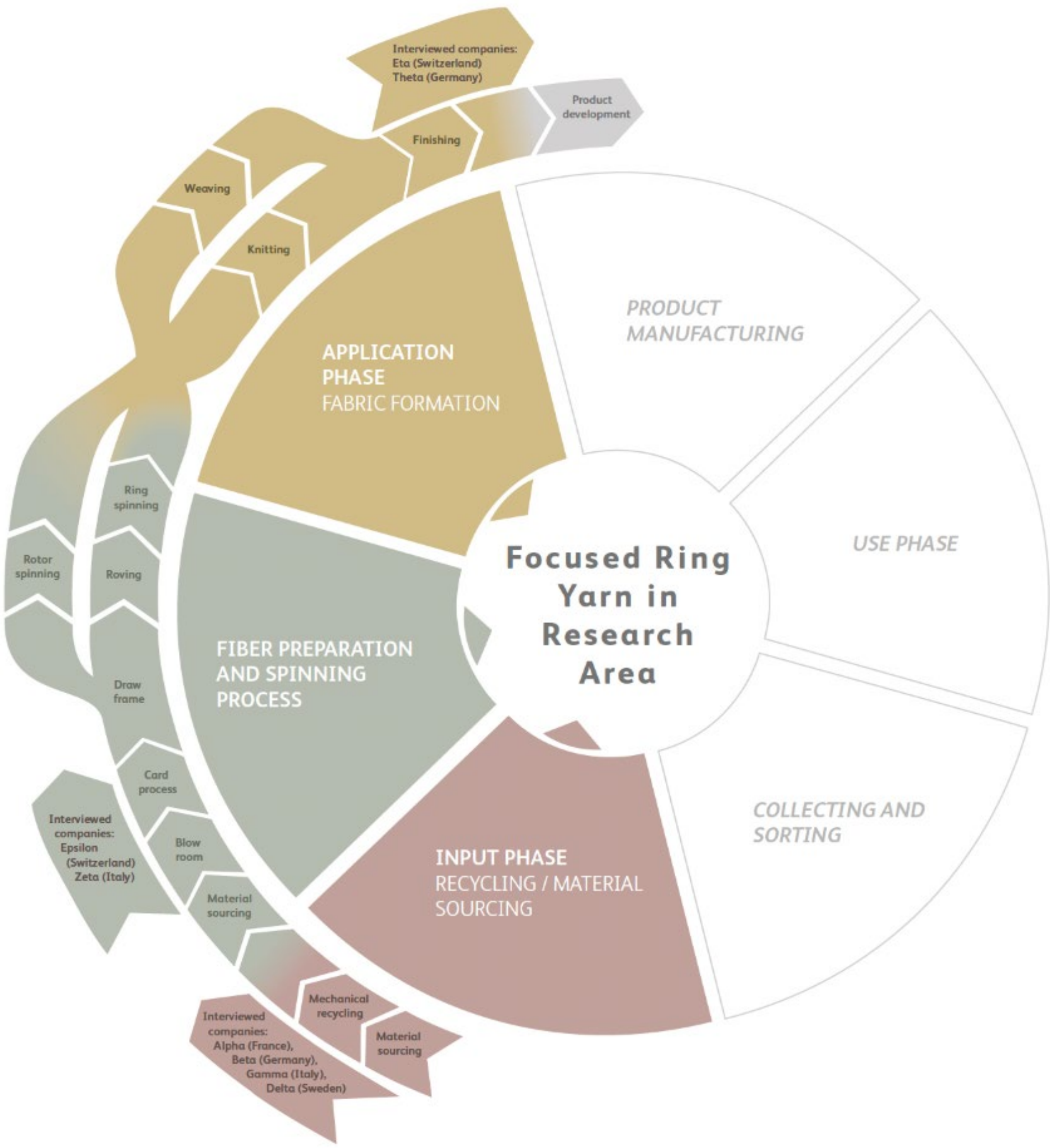


Table 1: Overview of the relevant process phases and anonymised partners for the individual case study. Process model based on Karell, 2019 in: Addressing the Dialogue between Design, Sorting and Recycling in a Circular

[22] Rieter https://www.rieter.com/fileadmin/user_upload/services/documents/expertise/textile-technology/rieter-special-print-recycling-3379-v1n-en_01.pdf, p. 9
[23] Melliand Textilberichte 4/2022

Findings of the input phase

Using the example of pre-consumer baker trousers made from poly-cotton[25], processed into a ring yarn[26], this chapter shows the interdependencies between and the challenges of recycling the raw material and the spinning process. The grey-white woven textile (PES 65%/CO 33%) was once part of a baker uniform. Like most workwear, this uniform was made from mixed fibres because of the high demands of its function and its cleaning requirements. Before the recycling process, all zips, buttons, and trouser pockets were removed from the trousers, the fabric was cut and reduced in size, and then it was mechanically recycled.

Figure 1

Figure 2

Figure 3

Figure 1 to 3: Baker trousers, removal of non-recyclable components and mechanically torn fibre material, © HSLU D&K

The spinning expert (Epsilon) described as follows the torn fibre material from the recycling process in an internal development protocol:

“There were many pieces of yarn left in the torn fibres. Removing or opening these pieces in the blow room or on the carding machine posed a great challenge. After removing 5% waste from the

[24] Karell, 2019
[25] Fabric made from a mixture of polyester and cotton fibre
[26] Most yarns made from staple fibres are *ring-spun* yarns. The structure of ring-spun yarns gives them visual, tactile, and aesthetic properties suitable for various end uses.

blow room and the carding machine, many white neps remained in the sliver. These white neps[27] did not fully integrate into the fibre structure and were carried on to the yarn and fabric.”

One difficulty in using post-consumer waste (PCW) recycled fibres in the spinning process is the increasing use of blended fabrics in our clothing.[28] While raw materials recycled from mono-materials such as wool or cashmere offer the highest recycled quality, blended textiles fall into the lowest category of recycled quality. These recycled grades are often used in the automotive industry as insulation materials. Post-industrial waste (PIW) is often used in recycling. In factories, 25 to 40% of all materials used either remain or become waste.[29] An important design aspect that affects the environmental performance of textiles is material composition, including the fibres used and their blends, or the presence of chemicals of concern that hinder the recycling of textile waste. These are easier to identify in PIW, in contrast to PCW. The origin and quality of mechanically torn fibres must have a balanced fibre index, whereby a short fibre content of 60% should not be exceeded. Information from recyclers on the expected purity of the raw material (fibre blend, yarn content, impurities) and information on the long-, medium- and short-fibre content would help spinning mills establish the proper processing settings, including the final spinning system or product concept. Another challenge is the damage to recycled raw material caused by the mechanical tearing process. This process damages the recycled raw material, resulting in a lower-quality fibre.[30] According to Sandin, this need not apply to other qualities in the final product, such as aesthetics or practicality, which are defined by the type of processing used and utility rather than fibre quality.[31] Sandin further argues that just because the mechanical recycling of fibres is downcycling in terms of the original fibre quality, it is not necessarily less beneficial from a waste hierarchy perspective than the recycling of polymers, oligomers or monomers. In a cascade approach, where textile waste is first sent to be mechanically pulped or for fibre recycling, mechanically torn fibre material may already be in an optimal state. Once the fibre length is reduced to a level where the material is no longer suitable for fabric or fibre recycling, it can be sent for polymer, oligomer or monomer recycling for other life cycles.[32] According to interviews with spinning experts, mechanical recycling is an established process which, from today's perspective, is more economical than chemical recycling processes.
In order to be able to optimise, in a design sense, the necessary process steps in the input phase, the following points are significant:

- Coloured recycled raw materials pose another challenge. Over-colouring, common in the recycling process, should be avoided by using an innovative design strategy. Karell recommends shaping the design process at sorting- and recycling-process level, because this is where the material and structural decisions on the products that will follow are made.[33] Sorting the raw material by colour is a key recycling process.
- The fibre length distribution and the short fibre content of the recycled raw material determine the blending ratio, the final spinning system to be used (ring or rotor spinning) and the subsequent application of the yarn in products. Design potential can be derived from this. Blends with higher short fibre content can naturally be processed well in the rotor spinning[34]

[27] A *nep* is a small knot of entangled fibres, usually comprising immature or short fibres.
[28] Elander and Ljungkvist, 2016
[29] Moora, R., H., Vihma, M. et al., 2021
[30] Karell, 2019
[31] Sandin, 2018
[32] Ibid.
[33] Karell, Niinimäki, 2019
[34] Compared to *ring-spun* yarn, the production of *rotor yarn* is bulkier, more elastic and absorbent. Unlike ring-spun yarn, rotor yarn it is made of short fibre. This factor increases production while reducing costs. Furthermore, rotor yarn enables using more recycling fibres than ring yarns.

process. In contrast, the standard ring spinning process requires a narrow fibre length distribution and a short fibre content similar to that of standard raw cotton. The selection of the blending raw material is not only an essential factor that must be matched to the end application but, at the same time, determines the aesthetics, function and sustainability potential of the yarns. Research potential exists in improving fibre lengths, function, aesthetics, and recyclability of the raw material.

	Input phase: Internal challenges affecting the spinning process	Input phase: External challenges affecting the spinning process
Design	- Sorting according to fibre quality, colour quality, and and technique - Blended materials and fibres are a challenge (blends of different materials, dyes, foreign objects like zippers) - Recycling of textile waste creates an almost endless amount of different raw material qualities	- Missing sorting categories for recycling processes - Lack of efficient and effective sorting technologies - Risk of chemical contamination - Economical efficiency cf. Waste Framework Directive, Extended Producer Responsibility (EPR)
Spinning	- Missing high opening degree while preserving the fiber length - Post-consumer fashion is the most challenging material (sorting/preparing) - Tearing 100 % CO garments creates a very high short fibre content (SFC) - Tearing cotton and MMF blends can help to gain a higher fibre length	- Lack of classification for recycled raw material (lack of information on origin and quality) - Lack of traceability and rapid identification of fibers using electronic chips, blockchain, and other technologies cf. Actions COM, 2022, 141 final

Table 2: Input phase with challenges for the design and spinning process

Findings in the spinning process

While sorting and recycling technologies need to be developed further, improving yarn design is the first step in overcoming technical challenges. For example, fibres are often mixed, which makes recycling difficult due to the low availability of technologies which according to fibre type. In addition, elastane, which is often added to increase the functionality of textiles, can act as a contaminant in almost all recycling processes. As a result, it harms the recycling process's economic feasibility and increases environmental costs. In the case of poly-cotton ring yarn from pre-consumer waste, the raw material was mixed with cellulose fibres (Refibra, Lenzing) in a 50/50 ratio, taking into account later applications. A careful balancing of aesthetics, functionality and recyclability of the yarn is needed in order to comply with the Global Recycling Standard, which requires a minimum of 50% recycled material in the final product.
According to the spinning expert, the card sliver[35] contained many white neps located on the surface of the yarn and which were not integrated into the yarn body. What is certain is that the quality of the ring yarn described above differs from 100% virgin fibre ring yarns, and does not currently meet comparable standards. In principle, standardisation helps to maintain comparisons of key parameters along the entire value chain: from raw fibre to card slivers and roving to finished yarn and beyond. They provide weavers, knitters, yarn merchants and retailers with the framework to specify and achieve the required quality. However, as such standards are oriented towards yarns made from virgin fibre, yarns made from recycled materials inevitably fail to meet the quality standards or are not available for recycled materials.

[35] Loose, untwisted bundle of fibre that is used to spin yarn. A *sliver* is created by carding the fibre. *Carding* is a mechanical process that disentangles, cleans and intermixes fibres to produce a web or sliver suitable for subsequent processing.

Another design focus within the spinning process is the definition of proper application contexts for recycled ring yarns and their yarn properties in terms of aesthetic, qualitative and functional attributes.[36] Yarn properties are often created using material blends. Within the cradle-to-cradle principles, mixing technical and biological materials or, as in the case described here, the fibres, is identified as problematic.[37] Moreover, the Ellen McArthur Foundation butterfly model follows the cradle-to-cradle approach with a biological and technical cycle. In the context of fibre blends, this means that natural and synthetic materials should not be combined, which often does not correspond to the current handling of fibre blends in yarn production.

Material blends in the textile recycling process can be identified on five levels:

- In the raw material extraction phase
- In the mixing chambers of the recycling process
- In yarn production
- In textile manufacturing
- In the product manufacturing phase

This paper focuses on blending at yarn level, with Table 4 showing the relevant blending processes in textile manufacturing. Initial fibre blending takes place in the blow room[38] during the spinning process. Further blending may be carried out on the draw frame[39] and during the twisting process[40]. As with all blending strategies, the aim is to optimise compliance with the requirements of the final material, on an aesthetic, functional, qualitative, and/or price level. These strategies offer excellent design potential.

---

[36] Sandin, 2018
[37] Braungart and McDonough, 2002
[38] The *blow room* is the first step in the spinning process. The compressed fibre bale is turned into a uniform mass by opening, cleaning or mixing.
[39] The sliver is blended, doubled, levelled, and drafted on the *draw frame*.
[40] In yarn production, *twisting* binds fibres or yarns together in a continuous strand.

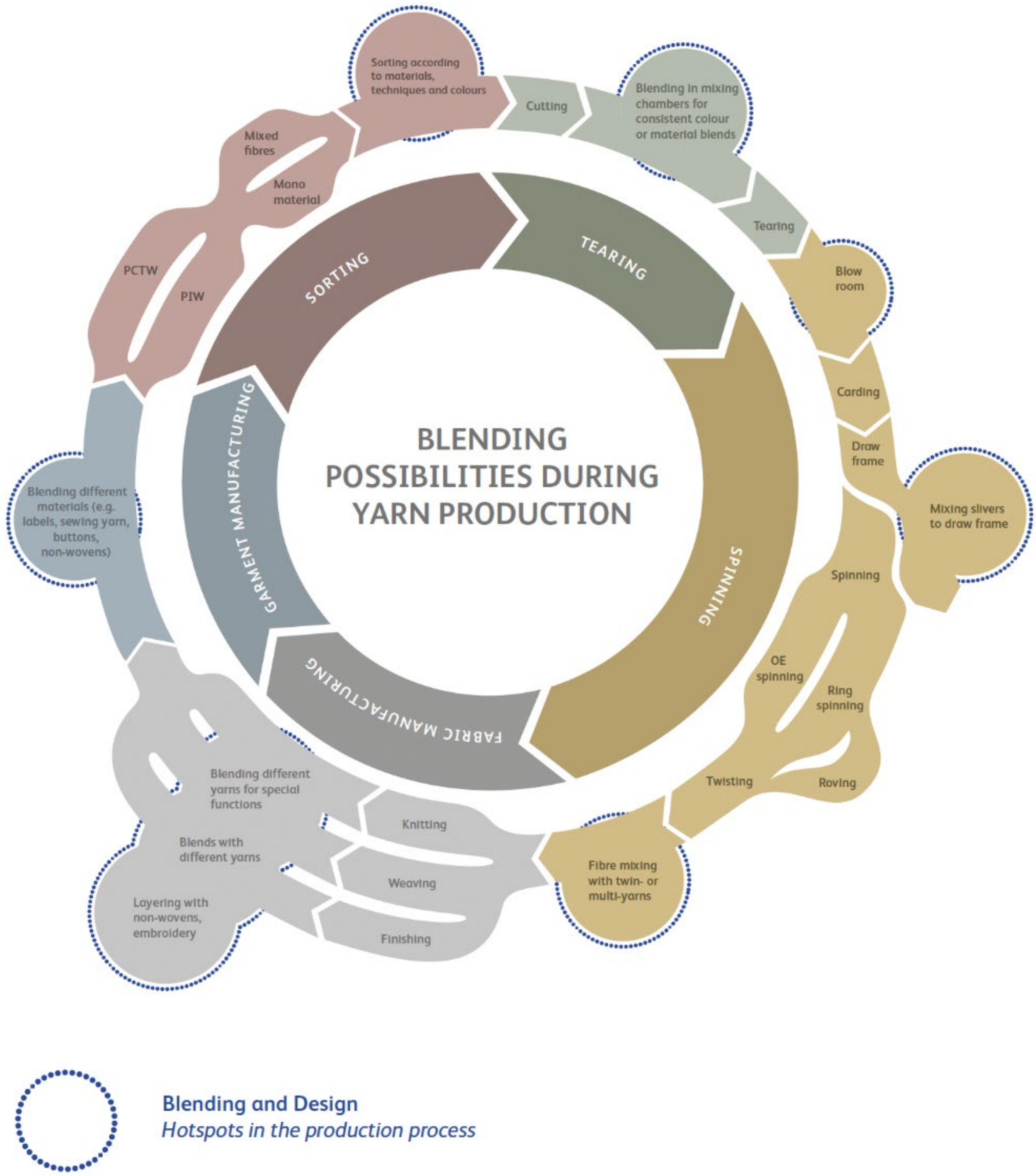


Table 3: Blending possibilities during yarn production, © HSLU D&K

Figure 5

Figure 6

Figure 7

Figure 8

Figures 5 to 8: Poly-cotton tear fibres mixed with Refibra^{TM} [41], sliver, roving[42] and final yarn, © HSLU D&K

The blending process of the poly-cotton yarn sets the material composition with recycled raw material from the input phase. The high short-fibre content is an important reason why fibres are blended, both in this example and recycled fibres in general. The fibre blend is crucial for the final spinning system to be used. Blends with higher short-fibre content can be processed well in the rotor spinning process. In contrast, the standard ring spinning process requires a narrow fibre length distribution and a short-fibre content similar to virgin raw cotton. Therefore, selecting a virgin fibre blend is a crucial factor that influences the end application and the process stability. While rotor yarns made from recycled fibres make up a large proportion of recycled yarns, the use of recycled fibres in ring yarns is lower.

- Mixing different types of recycled fibres (pre- and post-consumer) is commonly employed in spinning.[43] Pre-consumer fibres are taken in the manufacturing process and are cheaper than PCW, obtained through complex sorting, cleaning, and tearing processes. Pre-consumer fibres are also more consistent in terms of fibre type, colour, and structure, than post-consumer fibres.[44]
- In industrial processing, the blend proportions required are usually examined on a case-by-case basis. However, the lack of standardisation for recycled yarns and tear fibres leads to iteration

[41] Lenzing developed and patented the *REFIBRA^{TM} technology*, which involves wood pulp and cotton textile scraps.
[42] A *roving* is a long, narrow bundle of fibre used in the ring-spinning process.
[43] Hall, 2022
[44] Fontell and Hekikilä, 2017

loops and individual procedures, which make the processes and, ultimately, the products more expensive.

– Product concepts that take the properties of recycled yarns into account could boost their use as alternatives to yarns made from virgin fibres. It is essential, in addition to recycled rotor yarns, ring yarns with recycled content to increasingly enter the market in order to be able to serve a broader product range. Ring yarns accounted for 65% of global yarn production in 2017.[45] While rotor yarns have the advantage of being able to process a more significant proportion of recycled fibres, ring yarns are necessary so as to guarantee required strengths and to open up new markets and products.

	Spinning process: Internal challenges	Spinning process: External challenges
Design	- Blending according to aesthetics, functionality, quality, and recyclability of yarns - Blending to obtain material value - Combining different waste types, such as pre- and post-consumer textiles	- Choice of materials for accurate yarn idea: durability, reliability, reusability, upgradability, reparability, possibility of maintenance and refurbishment, resource use or resource efficiency, recycled content, possibility of remanufacturing and recycling, possibility of recovery of materials, environmental impacts, including carbon and environmental footprint cf. COM(2022), 142 final, Ecodesign requirements - Following standards such as Global recycling standard https://certifications.controlunion.com/de/certification-programs/certification-programs/grs-global-recycle-standard
Spinning	- Heterogeneity of textile waste fibres, high short fibre content and neps - Type of blending fibre and ratio must be chosen according to spinning technology and required yarn quality - Customised manufacturing processes due to missing material and design strategies - Lower speed, yarn breakage, fibre loss - Challenges related to durability (use of mechanically recycled fibres can have a negative impact on technical service life or quality in yarns) - Ratio of virgin material must be increased with a higher Short Fiber Content - Higher waste levels/higher soiling tendency - Rotor yarns can achieve same yarn quality compared to yarns made from 100 % virgin material while ring spinning is much more sensitive to a high short fibre and nep content - Short fibre content must be limited in ring yarns (Short Fibre Content max. 40 % in the blend)	- Blending considering quality standards eg. Uster Standard, https://www.textilegence.com/en/uster-statistics-the-common-language-of-textile-quality/ - Yarn specifications lack of digital data passport for recycled yarn cf. COM, (2022), 142 final - Lack of traceability of chemical content cf. ECHA, REACH, https://echa.europa.eu/de/home

Table 4: Challenges in the design and spinning process

Findings in the application phase

Hall identifies the material sourcing (recycling process) and blending (spinning) phases, as well as determining the application context, as key research areas for design.[46] Determining the appropriate application for the poly-cotton recycled yarn discussed here impacts the targeted products' durability, function, and aesthetics.

The Ne20 poly-cotton ring yarn was used to design a sports sock. For reinforcement, a recycled polyamide was processed with the poly-cotton ring yarn. The recycled content of the final product is 70%, well above the 50% in the GRS standard. In addition, material characteristics, such as melange[47], can be easily incorporated into the sock, which is particularly suitable for sock applications.

[45] ITMF, Rieter, 2017, https://www.rieter.com/fileadmin/user_upload/services/documents/customer-magazines/link/72/rieter-customer-magazine-link-no-72-88317-de.pdf
[46] Hall, 2022
[47] A *melange* yarn is produced with various combinations of coloured or raw white fibres (multi-coloured yarn).

In the example of the socks, the advantage of a more sustainable use of raw materials is offset by a shorter product life of the end product. In the case of the sock, the product life was measured using the abrasion resistance and pilling resistance Martindale method in accordance with ISO 12947-2:2016. According to the data, the sock produced comparable values to socks made from natural fibres. Due to their frequent use, socks are relatively short-lived products and are suitable for applying recycled yarns, among other things, because the knitted structure can conceal irregularities in the yarn. According to Goldsworthy (2017), to improve the environmental costs per wear of a relatively short-lived product, the material and production impacts could be reduced, for example, by using renewable energy and recycled materials. Life cycle assessment studies in Mistra Future Fashion have calculated "impact per wear".[48] In other words, it does not matter whether a garment is worn ten times in one year or ten times in five years. It is the "number" of uses before the end-of-life that is important from an ecological point of view. Therefore, the way we think about the lifespan of products in the design process is important.
Another implementation with potential was the use of poly-cotton recycled yarn in warp and weft in fabric. In contrast to the knitting application, the speed of the weaving machine had to be adjusted here. Furthermore, the high number of neps impaired the weaving process and led to thread breaks. The feedback from the application partners regarding fabric quality indicates a need for further optimisation in terms of process stability in industrial production (weaving) and the optical appearance of the twill. Despite good abrasion and pilling tests, the fabric did not form a homogeneous surface and did not meet expectations. In order for yarns made from recycled fibre blends to achieve market acceptance, technical hurdles have to be overcome, and optical requirements must be clarified with designers, textile manufacturers and brands.

Figure 9

Figure 10

Figures 9 to 10: Socks made from recycled baker trousers, © HSLU D&K

[48] Goldsworthy, 2017

	Output Phase: Internal challenges	Output Phase. External challenges
Design	- Promoting the use of eco-friendly yarns/products through style, colour and storytelling - Design strategies in dealing with recycled material (integrating neps into structures): frequent requests to have same quality standards – new designs need to be found - Production based on recycled content - Ring yarns with a high amount of mechanically recycled fibres have a different yarn character – suitable applications must be defined	- Compliance with environmental standards (GRS) cf. https://certifications.controlunion.com/de/certification-programs/certification-programs/grs-global-recycle-standard - Design for ease of recycling (design for disassembly, understanding composition of materials, modular design, reducing hazardous substances) cf. COM, (2022), 142 final, Ecodesign requirements - Lack of quality standards or requirements for the functional properties of recycled fibres and yarns cf. COM, (2022), 142 final, Ecodesign requirements
Material Technology	- With a higher amount of mechanically recycled fibres the imperfections of the yarn increase, while the tenacity decreases - Impact on running performance and soiling of machines during production processes - Ring yarn is necessary to guarantee the strength required for the demanding care of products	- Abrasion and pilling tests cf. https://www.sciencedirect.com/topics/engineering/martindale - Missing digital product/material passports, labels, etc., with detailed product content data containing all relevant recycling information - Minimum criteria for green public procurement for recycled content in textiles (where it does not affect lifetime) cf. COM, (2022), 142 final

Table 5: Challenges in the output phase (manufacturing of clothes) that affect the design and spinning process

Discussion

The new EU regulations for transitioning from a linear to a circular economy will be systemic and profound. The example of post-consumer baker trousers described here highlights specific findings regarding the external regulatory influences in the design and spinning process. However, this paper only gives a small insight into the state of research on the circular economy of textiles from design and spinning perspectives. Furthermore, product manufacturers, users and used textile collectors were excluded from the investigation due to their specific focus, which can be seen as a limitation in addressing systemic challenges. Nonetheless, the aim was to expand the state of research from the design and the spinning perspectives based on real experiences, and to initiate a discussion about this here.

In principle, spinning yarn from the poly-cotton recycling blend was possible. Further processing into knitted and woven goods also worked. The trials can be considered positive in principle but showed the need for further improvements and optimisation at all process levels: from ripping to spinning and beyond to fabric production and end use. Future research in yarn development using recycled fibres should therefore focus on the following aspects:

– Further optimisation of the tearing process. A gentler tearing process with a higher degree of fibre opening is important, especially for ring-spinning applications. Cooperation with ripping mills or machine manufacturers is essential.
– Fibre length distribution and short-fibre content determine the blending ratio and the final spinning system. Therefore, the selection of blend fibres is an essential factor that must match the end application. An optimisation of fibre lengths can be generated by adding fibres which are as similar as possible to fibre lengths from virgin fibres.
– In general, the quality of knitting and weaving yarns corresponds to their yarn structure, achieved due to the different degrees of twist. Unfortunately, there currently needs to be a comparative, standardised recycling database.

The investigated ring yarn can be used in the knitting sector and is suitable for scalability. By carrying the plating yarn along in the knitting process, the durability and wearing comfort of the sock are optimised. However, at the same time, a return to another recycling loop is prevented. One thing is sure: the appearance of the sock differs from comparative products made from virgin fibre material. The slight yarn unevenness and the neps show that a blend of 50% recycled fibres leads to a specific yarn structure with character. Therefore, it is crucial to know the quality and design requirements of the intended product.
Are the characteristics of the recycled yarn perceived as defects? Can a product made from a recycled material be a substitute for a product made from virgin fibres? Or should the "new aesthetics", the slight irregularity in the visual assessment of the products, be emphasised? Yarns made from recycled material require an interactive design approach, a reaction to the characteristics and properties of the recycled yarn in contrast to the usual acting with yarns made from virgin fibres (reacting vs. acting). Therefore, a clear product vision is required to integrate the aesthetics and function of the yarn into products. The questions are, therefore, what can the material do, what characteristics and features does it bring to the table, and what design strategies can be used to create an optimal product? Design research on material and product strategies can make a significant contribution to these ends.

Input phase (recycling) - Material purity or possibilities for material separation - Efficient and effective sorting technologies (e.g. RFID chips) - High opening degree while preserving the fibre length - Global quality standards applicable to recycled fibres
Yarn production - Focus on concepts on how to deal with different properties of recycled fibres: length, strength, composition, colours, and and how to use these properties in different yarn/products - Choice of material: focus on mono-material, focus on the use of bio-based materials such as cellulosic fibres, bio-based man-made fibres, bio-based marine fibres and protein fibres - Blend process: Use the suitable blend fibres to achieve desired yarn character (Combination of virgin and recycled fibres) Create colours without additional dying process Combine different waste types, such as pre- and post-consumer textiles - Design for recyclability: use fibres that are easy to recycle and reduce the use of multi-fibre blends - Optimise spinning technology in rotor or ring spinning
Output phase (manufacturing products) - Design for appropriate lifespan: build an understanding between design for longevity and design for recycling - Provide information on textile products (digital product passport) to guide consumers - Find suitable fields of application for recycled yarns - Realisation of mono-material products or easy separation of multi materials - Define new standards and applications for recycled yarns together with designer, weavers & knitters

Table 6: Recommendations for the design and spinning process using recycled fibres

Conclusion

This article focuses on the spinning process using recycled fibres and fields of action, design and research that arise from it. The challenges affecting the spinning process using recycled fibres not only concern questions of design or technical aspects in the manufacturing process: they also include external influences, which can be systemic, economic, and information-related. These challenges cannot be addressed by a single group or at a single point in the value chain. However, there is often a need for a shared understanding of what the individual actors want and what they can do, on the one hand, and what can be done using recycled material, on the other. Therefore, successful spinning design requires an active and open dialogue between recycling companies, spinning experts, fabric manufacturers, and brands. Regarding the material properties of recycled fibres and/or yarns, an interactive process (reacting vs. acting) is required from designers. The question of fibre properties or the specific characteristics of recycled yarns is included in the product development.
Research cooperation between a university and textile producers developed a recycled yarn made from a pair of poly-cotton baker trousers and marketable products. This article acts as a reality check, showing prototypes where there is a need for action and where the right course can be set through design decisions.
For a recycling-positive view at user and producer level, approaches in prototyping must continue to be developed in order to take into account new processes and recycling aesthetics, and to further increase the acceptance of secondary raw materials.

References

Anonymised interviews with partner companies from the Texcircle research project, according to Table 1

Adler, F., Schmidt, L., Weber Marin, A. and Willi, B. (2021), Design Decision Tool für eine nachhaltige Produktentwicklung, DOI: http://zenodo.org/record/5127157

Adler, F. et al., 2022, Texcircle – Circularity for textiles: Ein Zwischenbericht, LORY, HSLU, in Design und Kunst, DOI: 10.5281/zenodo.6420873

Braungart, M., 2012, C2C Design Concept. C2C., available at http://braungart.epea-hamburg.org/en/content/c2c-design-concept, [Visited: 07.07.2022]

Eisenhardt, K.M., 1989, Building theories from case study research, Academy of Management Review 14:532–550

Elander, M. and Ljungkvist, H., 2016, Critical aspects in design for fiber-to-fiber recycling of textiles. Mistra Future Fashion report 2016: 1 Stockholm: Mistra Future Fashion, available at http://mistrafuturefashion.com/2016-1-critical-aspects/ [Visited: 07.07.2022]

Elander, M., Watson, D. and Gylling, A. C., 2017, Evaluation of business models for increased reuse, collective use and prolonged lifetime of textiles. Mistra Future Fashion report series. [Visited: 07.07.2022]

EMF, Ellen MacArthur Foundation, 2017, A new textiles economy: redesigning fashion's future. (pdf) Retrieved on 15.07.2022 from https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf, [Visited: 07.07.2022]

European Commission, 2022, Establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC, COM, 2022, 142 final, available at https://eur-lex.europa.eu/legal-content/DE/HIS/?uri=COM:2022:142:FIN [Visited: 07.07.2022]

European Commission, 2020, A new circular economy action plan for a cleaner and more competitive Europe, COM, 2020, 98 final, available at https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN, p.12 [Visited: 07.07.2022]

European Commission, 2019, The European green deal (pdf), COM, 2019, 640 final, available at https://ec.europa.eu/info/sites/default/files/european-green-deal-communication_en.pdf, [Visited: 09.08.2022]

Fontell, P., and Hekikilä P., 2017, Models of circular business ecosystem for textiles, available at http://ethica.fi/en/circular_business_ecosystem_for_textiles/, [Visited: 25.08.2022]

Goldsworthy, K., 2017, The speedcycle: a design-led framework for fast and slow circular fashion lifecycles, in The Design Journal, 20:sup1, S1960-S1970, DOI: 10.1080/14606925.2017.1352714

Hall, C., 2022, Design for recycling knitwear, a framework for sorting, blending and cascading in the mechanical textile recycling industry, University of the Arts London, Centre for Circular Design, available at https://www.researchgate.net/publication/357335007_Design_for_Recycling_Knitwear_a_framework_for_sorting_blending_and_cascading_in_the_mechanical_textile_recycling_industry, [Visited: 25.08.2022]

ITMF, 2017, Rieter Machine Works Ltd.,https://www.rieter.com/fileadmin/user_upload/services/documents/customer-magazines/link/72/rieter-customer-magazine-link-no-72-88317-de.pdf, p.24, [Visited: 30.09.2022]

Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences. International Journal of Design, 9(2), 35-54. (PDF) Material Driven Design (MDD): A Method to Design for Material Experiences. Available at: https://www.researchgate.net/publication/277311821_Material_Driven_Design_MDD_A_Method_to_Design_for_Material_Experiences#fullTextFileContent [Visited:21.03.2023].

Karell, E., Niinimäki, K., 2019, Adressing the dialogue between design, sorting and recycling in a circular economy, in Design Journal 22(sup1): 997-1013, DOI: 10.1080/14606925.2019.1595413

Karell, E., Niinimäki, K., 2020, Closing the loop: intentional fashion design defined by recycling technologies, in G. Vignali et al. (eds.), Technology-driven sustainability, available at https://doi.org/10.1007/978-3-030-15483-7_2

Kazancoglu, I., Kazancoglu, Y., Yarimoglu, E., Kahraman, A., 2020, A conceptual framework for barriers of circular supply chains for sustainability in the textile industry. Sustain. Dev. 28, 1477–1492, available at https://doi.org/10.1002/sd.2100

Köhler, A., Watson, D., Trzepacz, S., Löw, C., Liu, R., Danneck, J., Konstantas, A., Donatello, S. and Faraca, G., Circular economy perspectives in the EU textile sector, EUR 30734 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-38646-9 (online), DOI: 10.2760/858144 (online), JRC125110

Kooistra, K. J., Termorshuizen, A. J. and Pyburn, R., 2006, The sustainability of cotton: consequences for man and environment (No. 223), Science Shop Wageningen UR

Koszewska, M., 2018, Circular economy — challenges for the textile and clothing industry, in Autex Research Journal 18 (4), S. 337–347. DOI: https://doi.org/10.1515/aut-2018-0023

Latour, B., 1983, Give Me a Laboratory and I Will Raise the World, in Karin Knorr Cetina and Michael Mulkay (ed.) Science Observed Perspectives on the Social Study of Science, pp. 141-170

Lucerne University of Applied Sciences and Arts, 2022, Texcircle research project, available at https://www.hslu.ch/en/lucerne-university-of-applied-sciences-and-arts/research/projects/detail/?pid=5554, [Visited: 30.09.2022]

Miles, M. B., Huberman, M. A. and Saldaña, J., 2014, Qualitative Data Analysis: A Methods Sourcebook — Third Edition, Thousand Oaks, CA: SAGE Publications, Inc.

Moora, R., H., Vihma, M. et al., 2021, Designing for circular fashion: integrating upcycling into conventional garment manufacturing processes, in Fash Text 8, 34. https://doi.org/10.1186/s40691-021-00262-9

Niinimäki, K., Peters, G., Dahlbo, H. et al, 2020, The environmental price of fast fashion. Nat Rev Earth Environ 1, 189–200, available at https://doi.org/10.1038/s43017-020-0039-9

Niinimäki et al, 2016, Colours in a circular economy, Aalto University, www.trash2cash.eu [Visited: 10.06.22]

Patti, A.; Cicala, G.; Acierno, D., 2021, Eco-sustainability of the textile production: waste recovery and current recycling in the composites world, in Polymers 2021, 13, 134, available at https://doi.org/10.3390/polym13010134

Payne, A., 2015, Open-and closed-loop recycling of textile and apparel products, in Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing. Elsevier Ltd., available at https://doi.org/10.1016/C2014-0-00761-7

Sandvik, I.M. and Stubbs, W., 2019, Circular fashion supply chain through textile-to-textile recycling, in Journal of Fashion Marketing and Management, Vol. 23 No. 3, pp. 366-381. https://doi.org/10.1108/JFMM-04-2018-0058

Sandin, G. and Peters, G.M., 2018, Environmental impact of textile reuse and recycling — a review, in Journal of Cleaner Production, 184, 353-365, available at https://doi.org/10.1016/j.jclepro.2018.02.266

Schwippl, H., 2020, The increasing importance of recycling in the staple-fiber spinning process, Rieter Machine Works Ltd. Winterthur, Switzerland, https://www.rieter.com/fileadmin/user_upload/services/documents/expertise/textile-technology/rieter-special-print-recycling-3379-v1n-en_01.pdf [Visited: 09.08.2022]

Stahel, W., 2016, The circular economy, in Nature 531, 435–438, available at https://doi.org/10.1038/531435a

Textile Exchange, 2020, Preferred Fiber & Materials—Market Report 2020, available at https://textileexchange.org/wp-content/uploads/2020/06/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf, [Visited: 30.06.2022]

Textile Exchange, 2021, Recycled Claim Standard (RCS) + Global Recycled Standard (GRS), available at https://textileexchange.org/standards/recycled-claim-standard-global-recycled-standard/ [Visited: 30.07.2022]

Will, M., 2022, Ring- und Rotorspinnen recycelter Fasern: Herausforderungen und Empfehlungen, in Melliand Textilberichte, European Textile Journal, 4/2022, Jahrgang 103, p.151

Wulfhorst, B., Gries, T., et al., 2015, Textile Fertigungsverfahren, Carl Hanser Verlag GmbH & Co. KG p. 442-456., DOI: 10.3139/9783446458666, ISBN: 978-3-446-45684-6

Tables

Figures

Brigitt Egloff

Short bio: Brigitt Egloff is a lecturer and applied design researcher at the Products & Textiles Research Group at Lucerne University of Applied Sciences and Arts. Her research focuses on design, technology and sustainability, with the aim of gaining a holistic understanding of circular processes while supporting the implementation of interdisciplinary research projects with stakeholders along the textile value chain. The research also concentrates on the scope of action of textile material cycles as seen from a design perspective in projects such as Texcircle, CIMproW and Solar Design tools.

Prototyping a novel visual computation framework for craft-led textile design

Sylwia Orynek, **University of Leeds**
Briony Thomas, **University of Leeds**
Alison McKay, **University of Leeds**

Abstract

In traditional woven structures, longitudinal warp yarns are held in tension on a frame while transverse weft yarns are drawn through them. This arrangement secures the threads; however, it also fixes them to one geometrical plane. Manipulation of the warp threads has the potential to enable a more flexible shaping of woven structures, enabling generation of freeform textile architectures. However, established textile notation methods and the implicit nature of a craftsperson's knowledge restrict the availability of craft-led techniques of thread manipulation within cross-disciplinary undertakings. To address this, shape grammars are proposed as means for the systematization and dissemination of those techniques and the associated tacit knowledge.
This paper follows iterative cycles of contextual analysis and creative practice, which facilitate the continual refinement of a design prototype. Firstly, archival materials and drawings of thread manipulations were analyzed and described in terms of the spatial relations between individual components. A phase of hand-making allowed for implementation of those findings into a weaving practice, which generated new understanding of possible structural arrangements. These were reviewed and codified according to the principles of shape grammar theory, and a preliminary weaving grammar was formulated. Finally, the grammar was translated into the digital environment of Shape Machine, a Rhino plug-in for computing with shapes. Implementation of the grammar was used to verify and improve the framework by highlighting design qualities which were not previously considered. The new findings were reflected on, and the framework updated to include parameters deemed most relevant to the current stages of its development. This paper presents and reflects on the roles of prototyping in the context of exploring a novel approach to textile design through a craft-led research inquiry. Concepts of experiential and new knowledge are considered, together with methods of their application, explication, and translation into discreet communicable actions. Consequently, the study serves as an example of a successful implementation of craft practice within design research.

Craft; Textiles; Computation; Shape grammars

Recent scholarly interest in craft as a method of research has contributed to a revival of discussions surrounding the meaning of the word 'craft' itself. As a domain, craft is usually placed in opposition to other, better-defined fields (Adamson, 2018); it is most often described in relation to art, design, and mechanized or automated manufacture. However, a clear setting of boundaries between those areas has proven challenging thus far, especially considering the cross-disciplinarity of real-life practices.

Similarly, as an inherent aspect of many craft disciplines, making has gained recognition as a contributing source of knowledge within academic inquiry (Bier, 2009, Gürsoy, 2016, Nimkulrat, 2012, Niedderer and Townsend, 2014). In times where new, highly responsive means of design and production are becoming widely available, it becomes more relevant than ever and finds universal application across disciplines (Veliz Reyes et al., 2019, Fanfani et al., 2020, Noel, 2015). Moreover, it has been argued that craft processes are open-ended in nature and capable of building upon previous findings to generate new outcomes (Dormer, 1997a, Paterson and Surette, 2015). It is therefore of utmost significance to not only preserve the knowledge stored within craft practices, but also to distribute it for the sake of cross-disciplinary advancement (Pye, 1971, Noel, 2015). This research adds to these efforts by analyzing and systematizing techniques of craft-led textile manipulations, with the aim of developing and disseminating a system for generative design of textile structures.

The next sections introduce the background to this research, its approach, and outcomes, followed by an analysis of findings and concluding remarks. Firstly, the value of craft as a method of research is discussed and presented in an inter-disciplinary context, outlining the methodological approach of this study. Three practical research stages are described, accompanied by visual documentation of the process and preliminary reflections. The findings are analyzed, highlighting the role of prototyping in utilization and generation of knowledge, while the last section summarizes the significance and impact of this study in the context of design research.

Research background

To understand the mechanisms of crafting as means of carrying out research, it is crucial to determine the specific qualities of craft which play a role in the exploration and generation of new knowledge. This section introduces the proposed subject in relation to relevant theories and academic developments spanning the fields of craft, textiles, design, and computation.

Defining craft practice

In their attempts at defining the word 'craft', several theorists have proposed considering it as a verb rather than a noun (Paterson and Surette, 2015). In doing so, its dynamic nature and the resultant malleable and innovative qualities become emphasized. Additionally, this reframes the conversation on craft from tradition, function, or discipline to that of a universal methodology, a way of thinking through problems (Adamson, 2018, Dormer, 1997a, Nimkulrat, 2012). This, in turn, supports the idea of making as an active handling of physical matter and forces, rather than as application of a preconceived design to passive materials, as argued by Tim Ingold (2010). In his work on the principles of making, craft is depicted as perpetually in motion, changing under the control of the skilled practitioner. The active evolution of material can be corrected and redirected at any moment, which requires the bodily awareness and dexterity that craft knowledge implicates. While to the outside observer the tasks of a craftsperson might seem repetitive, each movement is an altered response to what occurred before it (Brezine, 2009, Fanfani et al., 2020, Ingold, 2010).

In the concept of 'making for' (Gürsoy, 2016, p.18), hands-on exploration of materials serves an active role in the process of 'ideation, representation and materialization'. Gürsoy frames the personal, sensorial experience as a form of information processing and proposes a framework of abstracting-materializing-abstracting, wherein the acts of cognition and making interlink and alternate. Like the well-established design theory of seeing-moving-seeing developed by Schön and Wiggins (1992), the framework indicates a shift from drawing to making or, in Gürsoy's words, 'from visual to spatial reasoning' (2016, p.40).

As the personal know-how of a craft practitioner cannot be fully expressed through conventional textual means, sections of it escape translation (Niedderer and Townsend, 2014). Consequently, visual means of presentation and communication can support more creative, sensorial experiences of complex information. In the case of textiles, embedding the tacit knowledge in design systems has the potential to not only improve its distribution but also establish a foundation for exploration of new forms (Dormer, 1997a, Harlizius-Klück and McLean, 2021). To best understand and utilize the generative potential of hand-based textile techniques, it is crucial to systematize and disseminate them across disciplines.

Craft computation

The scientific analysis of ancient and contemporary artisanal textile practices suggest an involvement of complex algorithmic and geometrical concepts in the construction and decoration of fabrics (Bier, 2009, Brezine, 2009). Hand-making has been reasoned as a logical origin of numerical conventions, while traditional hand-weaving techniques are considered as early precursors to the automated looms of the Industrial Revolution and, ultimately, the first computers (Jefferies et al., 2015). Thus, it was the process of methodical analysis and extraction of the rules of craft practice that, over time, led to advancements in the fields of textiles, manufacturing and computation (Pye, 1971).

Nevertheless, a review of relevant literature reveals wide-ranging incompatibility of existing computer-aided design tools with real-life creative practices (Jowers et al., 2008, Kucukoglu and Colakoglu, 2013, Harlizius-Klück and McLean, 2021, McKay et al., 2010) and consequent failure in fully utilizing their innovative capacity. In the context of textiles, improving fabrication techniques offers the potential to remove out-of-plane weaving limitations brought about by mechanized textile manufacturing processes and tools (Veliz Reyes et al., 2019, Brezine, 2009). An in-depth understanding of how weavers identify and transform emergent textile forms could enable creation of a design system which allows for less restricted investigations and synthesis of complex, freeform architectures (Knight, 2018). Additionally, if developed in line with the principles of craft practice, digital modeling and production tools could equip the maker with new, sustainable means of engagement with their materials (Veliz Reyes et al., 2019, Noel, 2015). The recognition of rules present in craft textiles and their notation through computational means could facilitate the switch to the hybrid, cross-disciplinary practices made possible by the digital era (Gürsoy, 2016).

Knight and Stiny (2001) argue that approaches to the computation of craft should reflect the computational characteristics of craft itself. Therefore, it should be non-classical in representation - visual or even sensorial, rather than numerical; and classical in process – allowing for ad-hoc manipulations, rather than focus solely on achieving results. One such method developed by Stiny (1975) is shape grammars – a computational framework for designing with shapes. Shape grammars are visual, yet allow for mathematical interpretation, making them suitable for use by artists, designers, and engineers alike. A small set of initial shapes and rules can be used to create a multitude of existing and new designs without the need for full predetermination of design components. The user remains in control of recognizing, selecting and manipulating emerging forms (Jowers et al., 2008, McKay et al., 2010). Grammars have been utilized in the process of craft computation (Knight, 2018), including basket weaving (Muslimin, 2010) and wire-bending (Noel, 2015), proving suitable for the exploration of the subject presented in this paper.

Craft-led textile practice

Arguably, only a selection of textile techniques has so far been utilized on an industrial scale, mainly due to the relative ease with which they can be automated (Pye, 1971, Brezine, 2009). Consequently, more creative approaches to textile making have not been documented in a way that supports their transmission and implementation by creatives, scientists, or engineers. Further analysis of historical materials can assist contemporary researchers and designers in detecting new methods and tools of textile production. This is especially significant in the case of craft practices, wherein tacit knowledge is inherently challenging to describe and, instead, often passed on through non-verbal means (Pye, 1971, Fanfani et al., 2020, Harlizius-Klück and McLean, 2021).

As a result of extensive documentation efforts, the mathematical rules of weaving are now well understood, partly due to their intrinsically binary nature. Other textile techniques, such as multi-axial weaving (Bilisik, 2012), knitting (Popescu et al., 2021), crochet (Kucukoglu and Colakoglu, 2013) and bobbin lace (Irvine and Ruskey, 2014), have also attracted interest and undergone scholarly analysis for the purposes of mechanisation and production of technical materials. Those which prove more challenging to classify mathematically and, consequently, automate have remained in the hobby crafts category (Brezine, 2009).

Craftspeople routinely experiment with their practice, hacking techniques and tools available to them (Irvine and Ruskey, 2014). Craft-led textile practice accommodates experimental approaches to making, wherein different techniques can be combined to achieve an outcome not typically accounted for by traditional manufacture. Based on the contextual review and personal craft practice of the first author, it is hypothesized that spatial manipulation of threads has the potential to enable freeform textile construction, characterized by irregularity and three-dimensionality of form. In search of hand-based techniques suitable for the exploration of this capacity, a range of methods was considered, including leno and open-reed weaving, twining, and sprang. This paper presents the process of prototyping a craft-led textile design framework based on the systematisation of sprang[1] structures specifically.

[1] Sprang is a method of interlinking longitudinal threads, wherein the structure is maintained through appropriate tensioning. It is kept taut during the making process by temporary placement of rods, worked simultaneously from top and bottom, and then secured by several diagonal threads woven into the middle where both sections meet.

Textile notation

Due to the distinct presence of textiles within automated industries, their mechanisms have been well studied and adapted to mechanical production (Dormer, 1997a). Weaving, as arguably the most industrialized method of fabric manufacture, required a consistent system of representation allowing for ease of communication and repeatability (Dormer, 1997b, Brezine, 2009). The 0, 1 binary format, wherein the numbers represent dropping and lifting of warp threads respectively, is a simple, yet accurate numerical depiction of the physical act of weaving (Fanfani et al., 2020, Harlizius-Klück and McLean, 2021). In textile design it is usually represented visually as a diagram of black and white squares corresponding to the up-and-down movement of individual threads (Figure 1a). Additional colors or symbols might be introduced to indicate multiple layers of warps or wefts (Figure 1b).

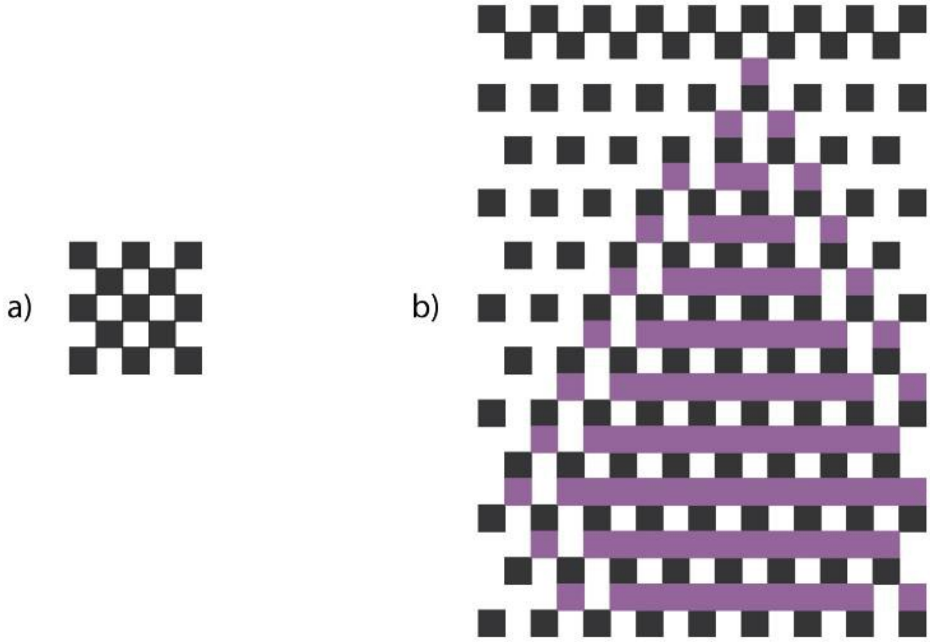


Figure 1: Examples of weave drafts: a - plain weave; b - pictorial extra weft

However, this method of notation does not reflect the performative nature of hand-weaving. Instead, it usually represents the resulting patterns, rather than the structural transformations taking place in the process of textile emergence. The weave drafts can be found insufficiently intuitive, requiring a high level of abstract thinking and familiarity with this method of notation, which is especially evident in the case of more spatially complex designs or freeform structures. Although the diagrams represent the rules of textile manufacturing algorithmically, they do not resemble the real-life practice of hand-weaving. Ideation and execution within a craft process are often intertwined and spontaneous, based on earlier transformations, sensorial perception, and reflection on emergent forms (Ingold, 2010). In comparison, weaving drafts seem simplistic and generalized to suit the common notational method, distorting the performative quality of textile making. They are better suited for presentation of final results, rather than exploration of potential designs. Moreover, historical making of cloth was often carried out without any notation, relying on the experience and dexterity of the craftsperson (Brezine, 2009). In the case of textile structures which have so far escaped technical documentation, physical samples, artifacts, and models provide a rich source of data on the assembly techniques involved in their production (Harlizius-Klück and McLean, 2021). It is therefore necessary to analyze and systematize the visual and tactile evidence to best disseminate the unspoken rules of craft-based textile arrangements.

Research approach

Inclusion of craft practices within research settings not only enhances contemporary design discourses, but also facilitates advancements in our understanding of craft as a means of material reasoning (Nimkulrat, 2012, Niedderer and Townsend, 2014). The craftsperson's in-depth understanding of the rigorous, technical principles of material properties and processes supports innovation through improvisation (Brezine, 2009). The ability to augment one's process at any point is what facilitates spontaneity, originality, and discovery; yet it concurrently introduces the possibility of continual failure (Pye, 1971). It is therefore essential for this exploration of 'the unknown' to be rooted in experiential knowledge which guides one's often subconscious and habitual, but controlled actions (Nimkulrat, 2012, Niedderer and Townsend, 2014). Only once the laws of a particular domain are fully comprehended, one gains the ability to manipulate them to their advantage (Dormer, 1997a, 1997b).

Craft processes rarely rely exclusively on hand practice but rather utilize a range of hand and automated or, in recent times, analog and digital tools (McCullough, 1998, Pye, 1971). It can therefore be argued that it is not a person's tools or materials that define their craft, but the physical and intellectual processes it involves. As such, a mix of both hand- and computer-based methods was employed in this research, under the methodological guidance of research-through-design and action research frameworks, which provide a structure to the complexity of a craft practice.

The research presented in this paper consisted of three separate stages with distinct practical outcomes, each testing and expanding on earlier results through a range of design- and craft-led methods: hand- and computer-based drawing*,* hand-weaving, and digital designing using Shape Machine, a Rhino plug-in for computing with shapes. The repeating cycles of making, reflecting, and analyzing continually refined the research outcomes by establishing a foundation for the next stage of explorations, eventually achieving the aim of this study (Figure 2). As such, prototyping within this craft research took on a form of creative reasoning through problems, a means of simultaneous development and testing. A more in-depth discussion of the processes and methods employed in this study is presented in the next section of this paper.

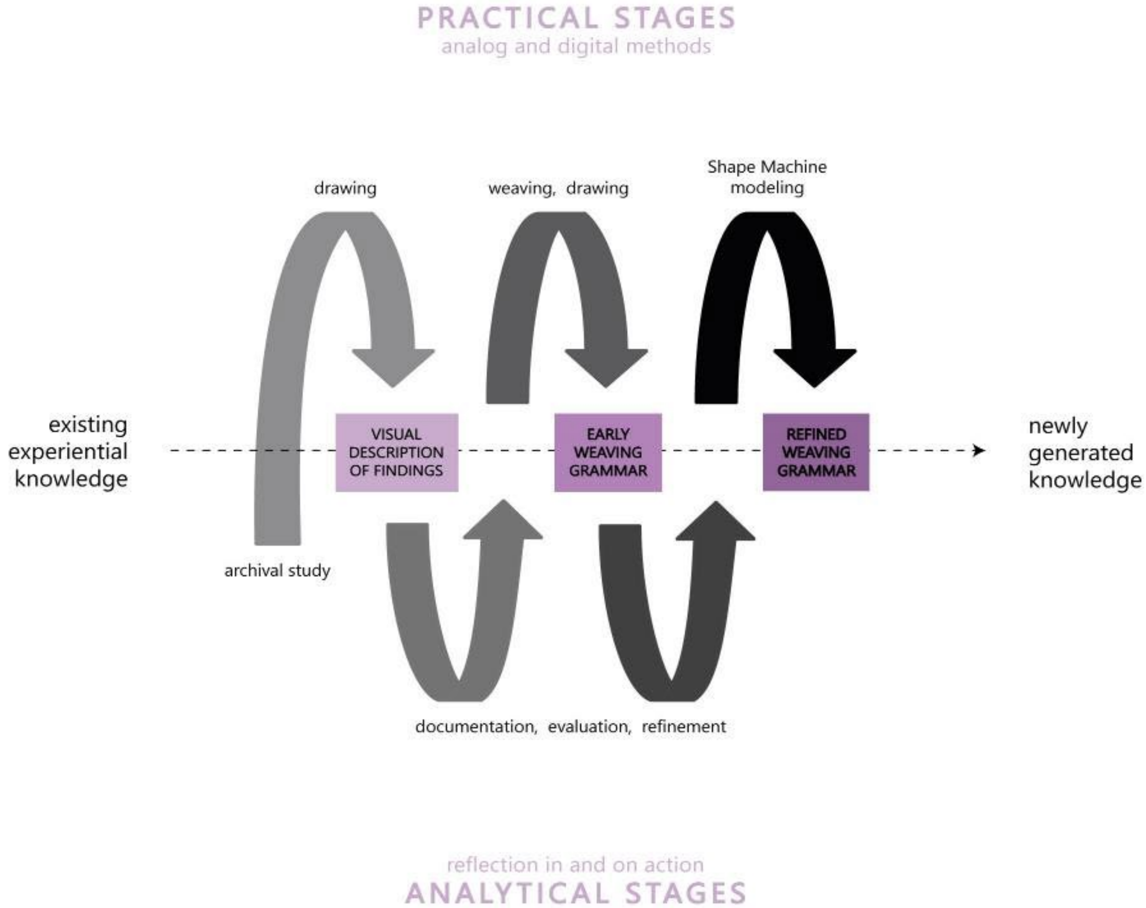


Figure 2: Diagram of research progression, methods, and outcomes

Research process and outcomes

This section introduces the outcomes of three practical phases undertaken as part of this study and discusses the methods employed at each stage in the context of craft-led research. It presents early reflections on the research process and its findings – from abstract to concrete - highlighting the gradual improvement of the design prototype and the resulting progression of knowledge.

Stage 1 – Analysis of textile techniques of warp manipulation

The first stage of the study focused on a contextual review of craft textile techniques. A range of hobby craft booklets, magazine articles and online blogs were examined, serving as 'how-to' guides for experimenting through hacking of hand-based methods and equipment. Terminology such as 'byways', 'off-the-loom' or 'fingers-as-tools' were found to denote the divergence and novelty within domestic craft practices, demonstrating their innovative capacity (Russell, 1975, Atwater, 1954).

The initial encounter with sprang was through purely visual means such as photographs, sketches, and diagrams which provided a theoretical insight into the new technique. Through the lens of existing knowledge of textile making and its notation, an initial assessment of sprang's suitability to the study of warp manipulations was made. This was then investigated in more depth through an archival review of the Collingwood Ethnographic Collection carried out at Crafts Study Centre, University of the Arts London. Here, a large amount of material samples and accompanying notes was studied to establish a cohesive understanding of the underlying rules of sprang construction. The haptic experience of materials facilitated a more comprehensive understanding of the spatial arrangements of individual threads and their relation to the structural properties of the fabrics. Samples which exhibited a variety and clarity of arrangements were selected as a foundation for further investigations through visual and tactile analysis, followed by a hand-based notation as means of exploring and testing the findings (Figure 3).

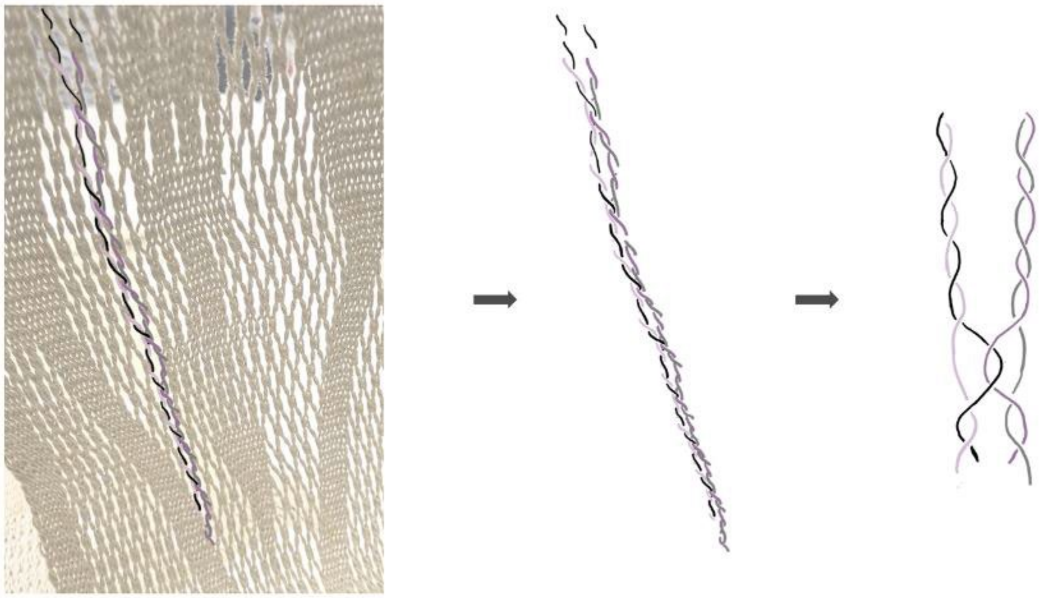


Figure 3: Study of sprang – from archival material to drawing

An assortment of sketches was made throughout and following the archival study which enhanced the processes of learning and subsequent experimentation with new structures. The findings were applied to a weave-like setting through a series of speculative drawings (Figure 4a) and exposed crucial structural differences in some of the thread arrangements (Figure 4b,c). Sketching was used as a means of processing and testing new information in the context of this research, while the digital diagrams served to communicate it visually.

At this point, a preliminary set of weaving rules manifested (Figure 5), visualizing the transformations taking place in the process of textile emergence. This developed intuitively but intentionally, as a result of previous drawing exercises, with the goal of achieving a more consistent grammar-like representation of warp manipulations. The early grammar was drawn by hand (Figure 5a), which was found most suitable for the exploratory stages of the design process. Translation into a digital format (Figure 5b) ensured a more uniform portrayal of the shapes in terms of their geometry, which enabled more systematic testing at later stages of the research and improved the communicability of the data produced.

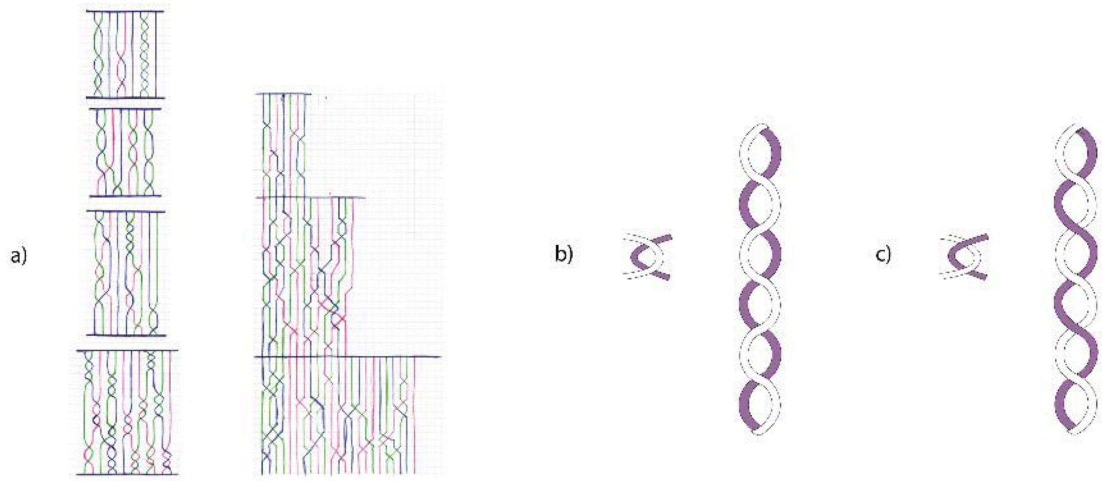


Figure 4: Early visual description of warp manipulations: a – hand drawings of warp thread switching; b–digital drawing of warp threads in leno-like structure; c - digital drawing of warp threads in sprang-like structure

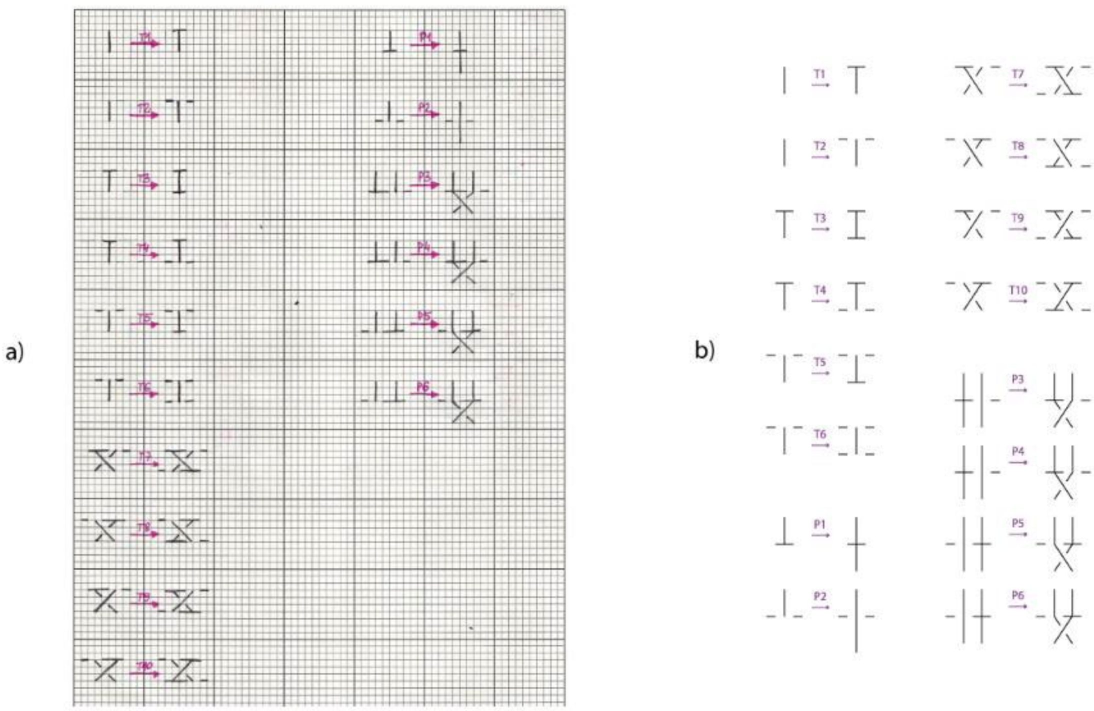


Figure 5: Early grammar-based descriptions of manipulations: a –hand drawings; b– digital drawings

Although the archival material provided sufficient information on the general principles of the studied technique, personal engagement with the findings reinforced the insight on its reinterpretation as a novel construction method. Sprang is not a method of weaving as it does not require diagonal threads to secure the structure; rather it relies solely on the tension of the longitudinal threads (Collingwood, 1974). To better understand its suitability to the subject of this research, the next stage aimed to determine how the sprang-based thread manipulations can be implemented into real-life weaving practice.

Stage 2 – Hand-based textile explorations of warp manipulation

Hand making, as an essential step in contemporary design practice, offers a sensorial, rather than purely intellectual, perception of materials which leads to a more thorough understanding of one's discipline (Ingold, 2010, Jefferies et al., 2015, Niedderer and Townsend, 2014). Correspondingly, making in this craft-led study played a role of spatial reasoning (Gürsoy, 2016) accompanied by reflection in and on action (Schön, 1983), where hand-weaving was used to test the notational format, directly informing further development of the grammar. Mechanisms of emergence in a top-down weaving setting were followed, where only the top warp ends were permanently attached to allow for flexible manipulation of the threads (Figure 6).

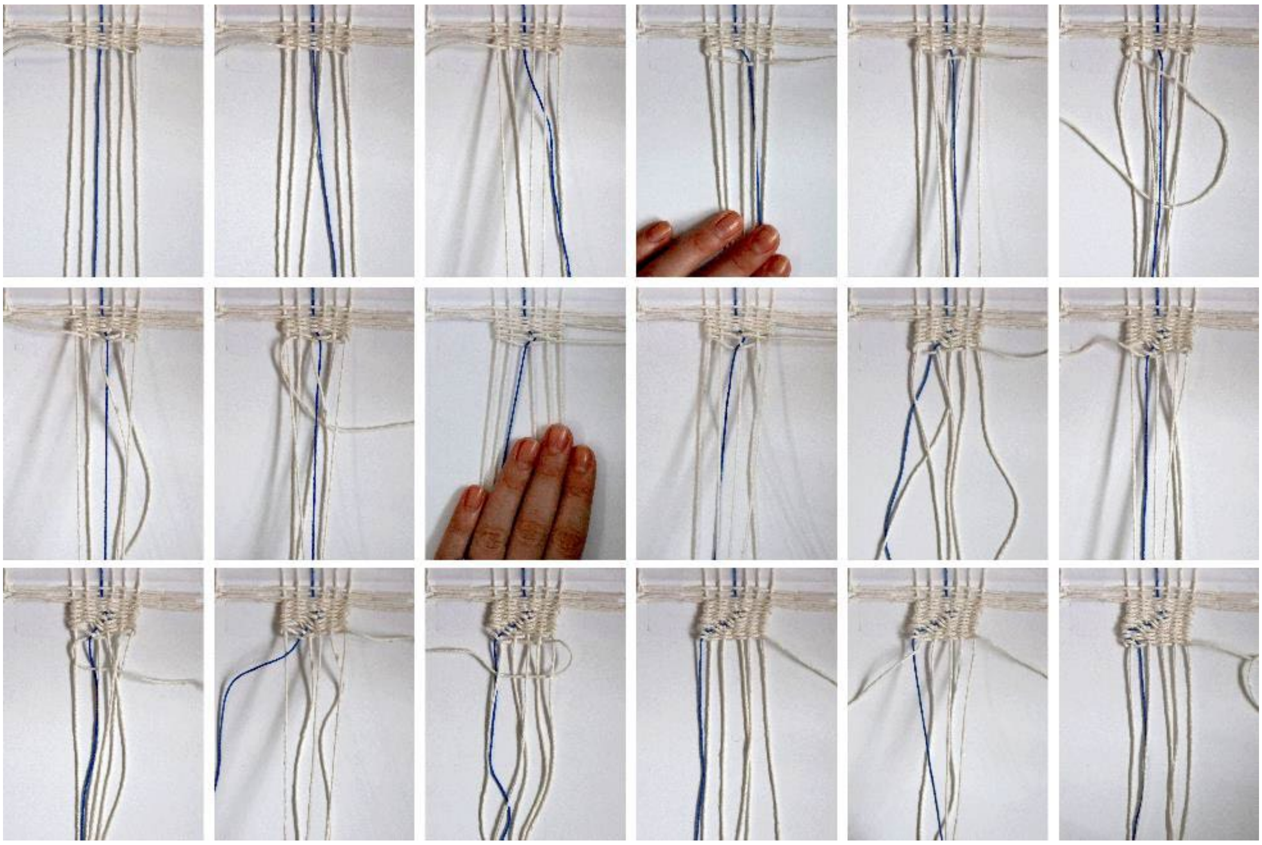


Figure 6: Progression of the hand-weaving process

To ensure rigor within the practical explorations, two criteria were set for the first phase of making: firstly, to maintain the plain weave structure throughout the sample, for which a selection of applicable rules was made; and secondly, to ensure the warp threads are secured in their new position after twisting, as some weft arrangements do not achieve this. While this was not perceived as an issue for certain applications, it narrowed down the initial testing space which prioritized structural integrity of the material.

The making phase was documented through a visual catalog of the weaving process, while the resulting material served as its tangible record. This prompted reflection on the undertaken practice and its outcomes, complementing the implicit evaluation and decision making which took place throughout the dynamic process of crafting. The sample was then additionally analyzed and tested through further sketching (Figure 7). Repeating the same movements in a different creative medium and switching from visual to spatial reasoning was both an exercise in the ongoing process of learning and a step towards embedding the resultant craft knowledge into a computational schema. Furthermore, drawing facilitated an effective translation of three-dimensional forms and movements into a two-dimensional format without distorting the craftsperson's experience of them.

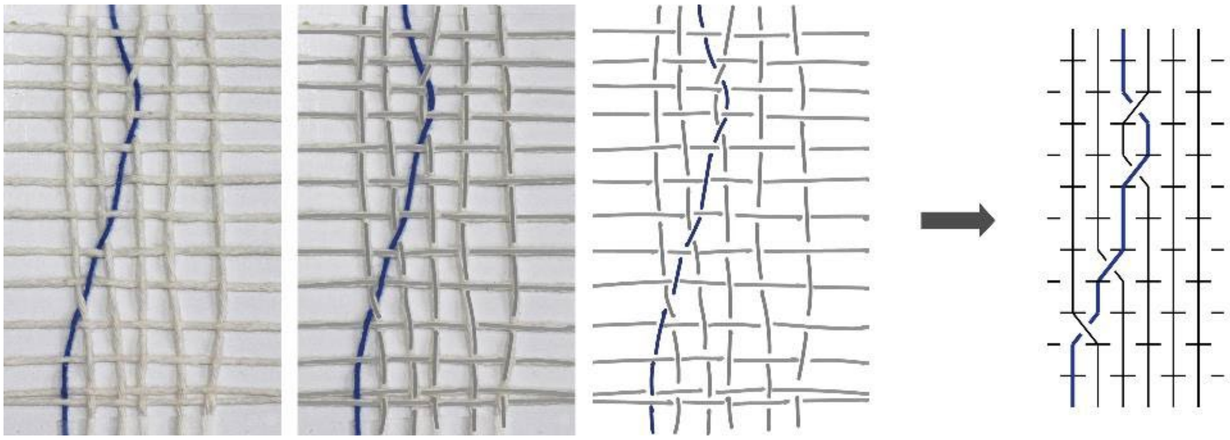


Figure 7: Progression of visual descriptions from hand-woven material sample to grammar-based structure

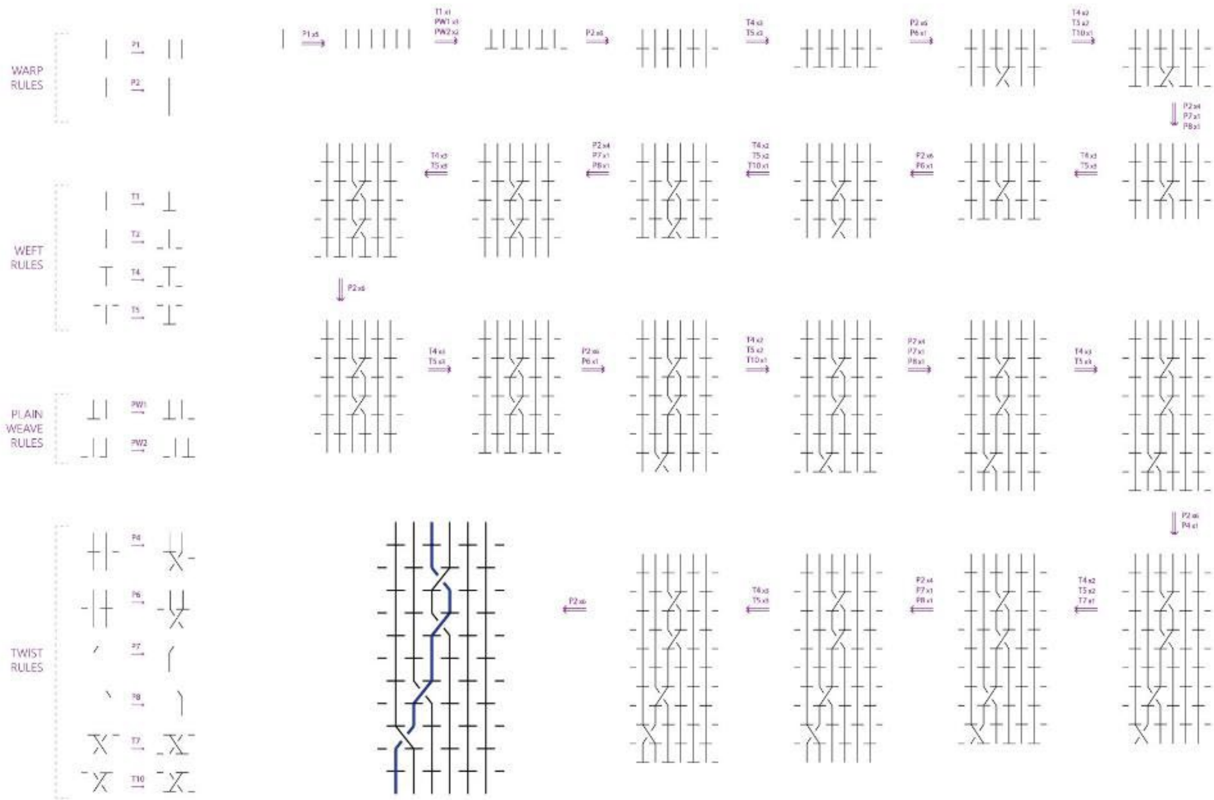


Figure 8: Grammar rules and emergence based on hand-woven material sample

The progression from material to hand sketch to digital drawing concluded with a visual representation in line with the principles of the previously set grammar. The resulting diagram of the structure was then used as a fixed design to be replicated through grammar-based processing (Figure 8). The transformations were drawn out in the sequence of emergence observed during the hand-weaving practice, which amplified the clarity of the distinct transformations carried out by the weaver as represented by the shape rules.

This stage of the research project utilized experiential knowledge in new contexts, which generated a new level of understanding of the craft practice, while sensory feedback from materials facilitated a more comprehensive experience in line with the principles of craft-based learning. Findings from the previous stage were tested in practice to ensure their applicability to real-life settings, enabling further refinement of the framework prototype. New, previously unconsidered parameters, such as the behavior of weft threads in relation to warp thread manipulation, were identified and fed back into the next iteration of the grammar.

Stage 3 – Digital computing with Shape Machine

The final stage of this research phase comprised of, firstly, converting the analog and digital grammar drawings into the Rhino interface and, secondly, using Shape Machine as a tool for computer-based programming with shapes (Economou et al., 2021). Previous hand-based notational representation of the weave structures and their transformations proved especially useful as they facilitated a more straightforward implementation of the grammar into the software environment. To better understand the operating principles of the Shape Machine, a range of preliminary tests was undertaken with traditional weaving transformations only.

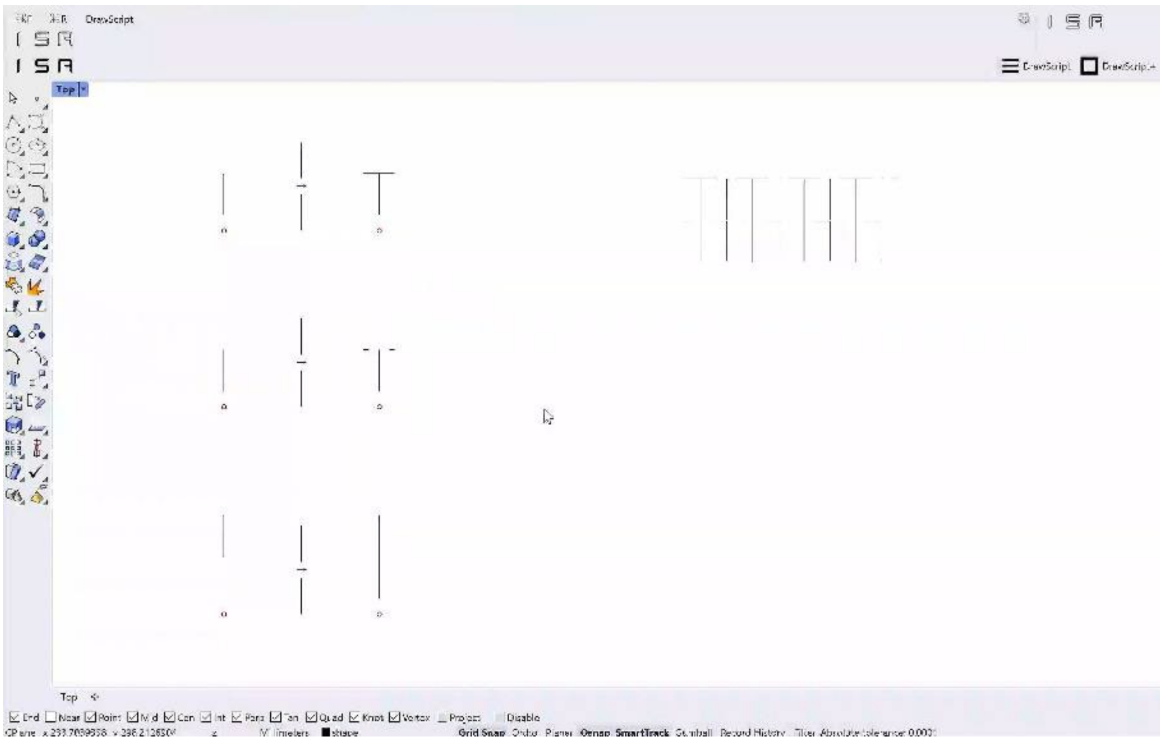


Figure 9: Shape Machine: grammar rules and emergence in a traditional weaving set up

Within the Shape Machine interface, an empty rule template is readily available to the user and includes the left-hand side, denoting the initial shape, the arrow as a sign of transformation, and the right-hand side, indicating the new shape. The first task was to draw out the weaving rules necessary for producing a plain weave structure; as shown in Figure 5, this initially included six weft rules (T1-T6) and two warp rules (P1-P2). However, through the process of testing, this decreased to just three rules – two weft rules and one warp rule (Figure 9). This was achieved thanks to the software's ability to recognize and convert independent sub-shapes contained within more complex designs and, consequently, require less data to process a computation. This tested and improved the grammar prototype both in and outside of the Shape Machine environment, reduced its complexity and increased efficiency of further developments.

As Shape Machine allows for a range of visual transformations (Economou et al., 2021), all were explored at this stage. Eventually, a set of plain weave structures was produced using the isometric function which maintains the form and size of the initial shapes. This setting was concluded as most applicable for this phase of the research because it ensured continued coherence of the computations to the mechanisms of the craft-led textile practice observed in previous stages. However, a number of potential alternatives were encountered and noted to be considered in the future.

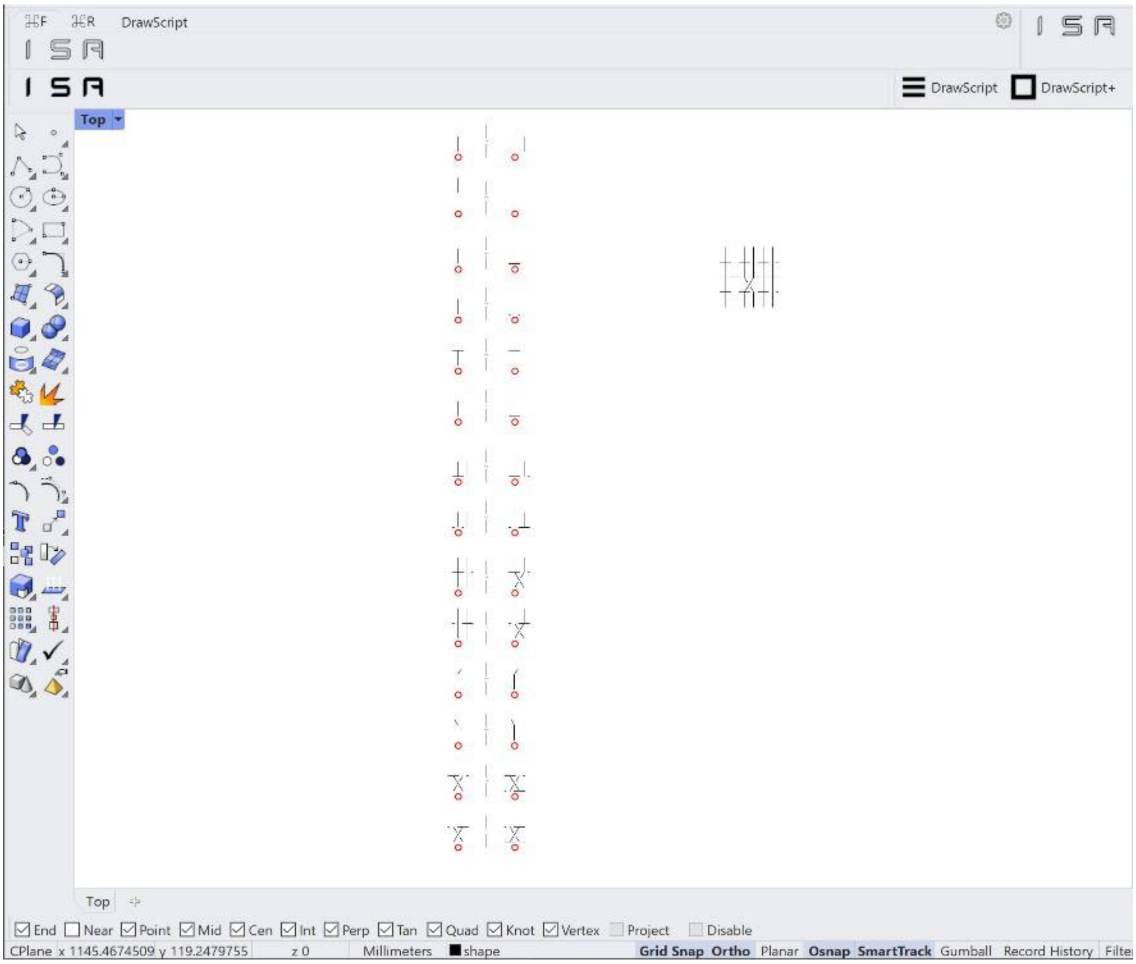


Figure 10: Shape Machine – mock-up design of grammar rules and emergence including warp manipulations

The next step attempted to apply the Shape Machine workflow to warp thread manipulations. The set of rules used for plain weave structures was extended to include the twisting transformations (Figure 10). Following on from the previous iterations of the grammar prototype (see Figure 8), a set of rules (T4, T5, PW1 and PW2) was used which limited the weft arrangements to plain weave structures only. Early computations identified inconsistencies in sub-shape recognition which prompted a reconsideration of appropriate shape representation within the Rhino environment. Additional testing should be carried out to ensure successful implementation of the analog grammar into this programming software.

Nevertheless, the Shape Machine provided an unbiased perspective for generation of designs, which could then be analyzed and discarded or developed further by the user. It highlighted the importance of uniform representation of shapes and sub-shapes in developing a visual computation system. Furthermore, by offering different geometric options for searching and transforming shapes, the Shape Machine introduced a new angle to the development of the design framework. As such, it completed this phase of prototyping and set a foundation for further developments.

Reflection

The examples above outline the making, designing, and testing activities which were undertaken as part of a craft-led research process. In Stage 1, previous know-how of craft textiles served as a foundation for the contextual review and critical analysis, while archival study validated and advanced the development of a first design prototype. In Stages 2 and 3 prototyping took on the form of hand-based material manipulations and Shape Machine computer simulations respectively. Each stage was crucial in exploring and testing the subject of this research project, as it facilitated different forms of engagement and feedback. Archival study of materials provided an opportunity for a haptic and visual engagement with a new technique, reinforced by its analog and digital notation. A later phase of hand-making aided an application of the findings in practice, while computer-aided design exercises offered a more structured/systematic experience. The range of media used in this study required different approaches to creative reasoning and reflects the complexity of craft-based practice. As such, it enabled a more comprehensive review, testing and analysis of the proposed framework which was additionally reinforced by the iterative methodology.

Here, hand and computer-based drawing ran alongside the research activities as means of reflection-in-action, ideation, and documentation, but also continual testing and refinement of findings. In the early phases, it was used as a tool to explore the design space and to describe visually the mechanisms of hand-based textile making observed through contextual review. Moreover, drawing assisted in systematizing and explicating the complex, implicit actions undertaken during the weaving practice, while the Shape Machine introduced a new dimension to its pictorial notation. Consequently, it confirmed the suitability of the adopted approach to the computational design of craft-led textile structures.

As previously argued, craft knowledge is the basis of any craft practice; it serves as a foundation for creative exploration of a novel subject and facilitates the extraction of new findings (Paterson and Surette, 2015, Bier, 2009, Dormer, 1997a). In this study, the consecutive cycles of making and analysis transformed and refined the knowledge of the craft researcher, facilitating the next phase of development. Prototyping made use and tested the experiential understanding of a craft textile practice, while simultaneously producing new insights about the materials, tools and methods engaged with during the research process. The transformation of sensorial feedback into new knowledge required reflection in and on action (Schön, 1983), which related the newly discovered variables to previous experiences and relevant contexts. Both the seeing/sensing/abstracting (Schön and Wiggins, 1992) and the moving/materializing/making (Gürsoy, 2016) phases involved implementation and generation of knowledge, whether deliberate or intuitive, intellectual or tacit.

Both successful and failed outcomes provided useful information about the subject at hand; the experiences accumulated to establish a new, improved level of knowledge, which became the basis for the next stage of explorations. This process was dynamic and open-ended as it facilitated a continual refinement of knowledge throughout the process of craft research while not striving to achieve a complete form. As such, it is proposed that one's level of understanding of a craft evolves through the process of prototyping, wherein acting and reflecting interlink to continually refine the design.

Moreover, artifacts produced as part of this craft-led research are embedded with the knowledge involved in its process (Dormer, 1997a) and, as such, can be utilized as tools for documentation, clarification and communication of findings at different stages of creative exploration. Visual representation of craft-based textile structures through hand drawings, digital renderings and physical samples clarifies the craft researcher's implicit and sensorial understanding of them. The complex mechanisms of a craft process are depicted as distinct, computable actions, achieving the aim of their systematization and dissemination in line with the principles of craft practice.

Conclusion

This paper presents a process of iterative prototyping in the development of a visual computation framework for craft-led textile design. It introduced relevant theories in reference to craft practice, design processes and experiential knowledge, setting a theoretical and methodological foundation for its execution. In particular, it examined the recent increase in cross-disciplinary interest in craft methodologies and the role of making in knowledge generation (Gürsoy, 2016, Bier, 2009). This, in turn, identified shortcomings in the general understanding of the mechanisms of craft-led research and the role of prototyping within it. The paper engages with these concepts through a reflective textile design practice, addressing a wider gap within design research.

The contextual review within this study focused on cross-disciplinary undertakings which use computational frameworks to analyze and formalize craft-based construction techniques. Accordingly, this paper acknowledges the high cultural and generative value of these methods (Noel, 2015, Townsend and Niedderer, 2016, Harlizius-Klück and McLean, 2021) and argues for their preservation and distribution outside of the hobbyist sphere. It further comments on the innovative potential of craft-led textile techniques, while recognizing the difficulties in their distribution stemming from the tacit nature of craft processes. In response, the authors propose shape grammars as a means of systematizing and disseminating the hand-based techniques of textile manipulation and associated tacit knowledge.

The research was approached through a craft-based methodology and used prototyping as a method of discovery and iterative refinement of the visual computation framework. By considering and engaging with the premise of craft-based practice as a reflective one (Schön, 1983), this study contributes to the wider conversation on the role of prototypes within art and design research contexts. It provides an insight into the mechanisms of knowledge progression as a result of such a process – from applying existing experience in new contexts to generating new theoretical and practical concepts. Further, it comments on how new findings can feed back to the general pool of knowledge with which the next iteration of research is approached, complementing the dynamic and open-ended nature of craft practices.

Additionally, the craft-led prototyping confirms the applicability of hand-based thread manipulations to a weaving set up, facilitating further exploration and design of novel textile structures. Testing of the model grammar against real-life textile practice ensured its functionality; however, additional hand and computer-based investigations should be carried out to validate its further iterations. A finalized visual computation framework has the potential to not only disseminate the overlooked textile techniques across disciplines, but also form a foundation for development of novel structures and manufacturing methods.

Finally, the prototypes resulting from this study reflect the consecutive stages of the research practice and remain valuable as its records. They serve as static snapshots of an active process of discovery, as tangible reflections of the researcher's knowledge from a specific moment in time. They hold a wealth of information on the materials, tools and processes involved in craft-led research. If utilized further as visual, sensorial, or even interactive tools for the distribution of tacit knowledge, they could contribute to cross-disciplinary exchange and consequent advancements.

References

Adamson, g. 2018. Thinking through craft, bloomsbury.

Atwater, m. M. 1954. Byways in hand-weaving, the macmillan company.

Bier, c. 2009. Number, shape, and the nature of space: thinking through islamic art. In: robson e., s. J. (ed.) The oxford handbook of the history of mathematics.

Bilisik, k. 2012. Multiaxis three-dimensional weaving for composites: a review. Textile research journal, 82, 725-743.

Brezine, c. 2009. Algorithms and automation: the production of mathematics and textiles. In: robson e., s. J. (ed.) The oxford handbook of the history of mathematics. Oxford university press.

Collingwood, p. 1974. The techniques of sprang : plaiting on stretched threads, london, faber.

Dormer, p. 1997a. Craft and the turing test for practical thinking. In: dormer, p. (ed.) The culture of craft. Manchester university press.

Dormer, p. 1997b. Textiles and technology. In: dormer, p. (ed.) The culture of craft. Manchester university press.

Economou, a., hong, t.-c., ligler, h. & park, j. 2021. Shape machine: a primer for visual computation.

Fanfani, g., griffiths, d., harlizius-klück, e., mamidipudi, a. & mclean, a. 2020. (micro-)performing ancient weaving in the penelope project. Performance research, 25, 123-130.

Gürsoy, b. 2016. Formalizing making in design. Doctor of philosophy, istanbul technical university.

Harlizius-klück, e. & mclean, a. 2021. The penelope project: a case study in computational thinking. In: lydia schulze heuling, c. F. (ed.) Algorithmic and aesthetic literacy. Emerging transdisciplinary explorationsfor the digital age. Toronto: verlag barbara budrich.

Ingold, t. 2010. The textility of making. Cambridge journal of economics, 34, 91-102.

Irvine, v. & ruskey, f. 2014. Developing a mathematical model for bobbin lace. Journal of mathematics and the arts, 8, 95-110.

Jefferies, j., wood conroy, d. & clark, h. 2015. The handbook of textile culture, bloomsbury publishing.

Jowers, i., prats, m., lim, s., mckay, a., garner, s. & chase, s. C. 2008. Supporting reinterpretation in computer-aided conceptual design. Eurographics workshop on sketch-based interfaces and modeling.

Knight, t. 2018. Craft, performance, and grammars. In: lee, j.-h. (ed.) Computational studies on cultural variation and heredity. Singapore: springer singapore.

Knight, t. & stiny, g. 2001. Classical and non-classical computation. Architectural research quarterly, 5, 355-372.

Kucukoglu, j. G. & colakoglu, b. Algorithmic form generation for crochet technique a study for decoding crocheted surface behaviour to explore variations. Ecaade 31, 2013.

Mccullough, m. 1998. Abstracting craft: the practiced digital hand, the mit press.

Mckay, a., chase, s., garner, s., jowers, i., prats, m., hogg, d., chau, h. H., de pennington, a., earl, c. & lim, s. 2010. Design synthesis and shape generation. In: inns, t. (ed.) Designing for the 21st century

Interdisciplinary methods and findings. London: routledge.

Muslimin, r. 2010. Interweaving grammar: reconfiguring vernacular structure through parametric shape grammar. International journal of architectural computing, 8, 93-110.

Niedderer, k. & townsend, k. 2014. Designing craft research: joining emotion and knowledge. The design journal, 17, 624-647.

Nimkulrat, n. 2012. Hands-on intellect: integrating craft practice into design research. International journal of design, 6, 1-14.

Noel, v. 2015. The bailey-derek grammar: recording the craft of wire-bending in the trinidad carnival. Leonardo, 48, 357-365.

Paterson, e. C. & surette, s. 2015. Sloppy craft : postdisciplinarity and the crafts, london, bloomsbury.

Popescu, m., rippmann, m., liew, a., reiter, l., flatt, r. J., van mele, t. & block, p. 2021. Structural design, digital fabrication and construction of the cable-net and knitted formwork of the knitcandela concrete shell. Structures, 31, 1287-1299.

Pye, d. 1971. The nature and art of workmanship, london, studio vista.

Russell, e. 1975. Off-loom weaving: a basic manual, little, brown and company.

Schön, d. 1983. The reflective practitioner, routledge.

Schön, d. & wiggins, g. 1992. Kinds of seeing and their functions in designing. Design studies, 13, 135-156.

Stiny, g. 1975. Pictorial and formal aspects of shape and shape grammars, birkhauser verlag, basel und stuttgart.

Townsend, k. & niedderer, k. The role of craft in creative innovation: skin, cloth and metal. 2016.

Veliz reyes, a., jabi, w., gomaa, m., chatzivasileiadi, a., ahmad, l. & wardhana, n. M. 2019. Negotiated matter: a robotic exploration of craft-driven innovation. Architectural science review, 62, 398-408.

Sylwia Orynek

Sylwia Orynek is PhD candidate in the School of Design at the University of Leeds, whose doctoral project sits at the intersection of textiles, craft, and computation. With research interests spanning the fields of arts, design science, and engineering, she incorporates diverse approaches to investigate three-dimensional textile construction. In her academic practice she brings together archival study, making, and scientific methods to explore the value of heritage techniques and experiential knowledge in novel design frameworks.

Briony Thomas

Briony Thomas is Associate Professor of Design Science at the University of Leeds with a joint appointment across the Faculties of Arts and Engineering. Her research and creative practice focus on transdisciplinary arts-science initiatives with communities, maker-centred learning, and hands-on creative engagement. Briony is a University Public Engagement Champion and Chair of Leeds Cultural Education Partnership, a network of cultural, education and community organizations, committed to ensuring access to creative learning opportunities for all children and young people.

Alison McKay

Alison McKay is Professor of Design Systems in the School of Mechanical Engineering at the University of Leeds. Her research focuses on kinds of design systems, including shape computation and engineering information systems. Her research is positioned within the context of stage gate processes that typify current industry practice and aims to facilitate improved modes of working through the exploitation of digital technology and the establishment of design methods and tools.

Materials Libraries: designing the experiential knowledge transfer through prototyping

Alessia Romani, Department of Chemistry, Materials and Chemical Engineering “Giulio Natta”, Design Department – Politecnico di Milano
Valentina Rognoli, Design Department – Politecnico di Milano
Marinella Levi, Department of Chemistry, Materials and Chemical Engineering “Giulio Natta” – Politecnico di Milano

Abstract

Experiential knowledge plays a crucial role in exploiting new materials within real contexts, i.e., designing products and applications. As a result, understanding and transferring this kind of knowledge has gained increasing attention, as well as developing new experiential tools addressing this challenge.
This contribution investigates the role of physical prototypes in designing new experiential tools for the knowledge transfer of emerging materials and technologies, i.e., Materials Libraries. The analysis is performed through a reflective practice approach based on two practical case studies dealing with new materials from waste for 3D printing. The former Materials Library focuses on the recycling of composite materials from products at their End-of-Life in industrial contexts, i.e., wind turbine blades. The latter one, RepMat Library, is an ongoing experimentation that aims to develop an open source Materials Library to collect new 3D printable materials and applications from waste-based polymers and biomass involving distributed networks and local communities, i.e., makerspaces and fablabs.
After briefly explaining the two case studies, this work defines an outline proposal of the main contributions of prototypes in designing new Materials Libraries, which means: (i) generating and detecting the experiential knowledge to transfer; (ii) categorizing and defining the taxonomy of the tool; (iii) testing the experiential knowledge transfer; and (iv) speculating on new possible ways of using Materials Libraries. In short, prototypes were mainly used as a physical learning medium to preliminary tinker with materials and technology, as well as a validating tool for the interaction between the users and the library. Furthermore, prototypes may contribute to envisioning new ways of developing and using Materials Libraries to spread experiential knowledge, i.e., democratizing the design process of the tool by encouraging *distributed*, accessible, and collaborative work within local communities and distributed networks.

Materials Experience; Material Tinkering; Research through Design; Material Driven Design; 3D printing.

Experiential knowledge is a tacit and non-discursive way of knowing that originates from practical experiences and experimentation (Groth et al., 2020; Niedderer, 2007). Contrarily to other kinds of knowledge, it cannot be entirely articulated by textual or verbal media, and it often requires different non-textual approaches for its effective transfer, i.e., translating abstract concepts into tangible artifacts (Niedderer, 2007; Nimkulrat, 2021). Experiential knowledge has a crucial role in design practice. Designers often rely on hands-on approaches to build new practical knowledge for their professional activities, i.e., through samples and prototypes (Camburn et al., 2017). Furthermore, this kind of tacit knowledge is a powerful way to connect theory and practice, especially dealing with practical implementations of new products and applications. This approach has been recently linked to new emerging materials and technologies within the design field, fostering new practical inquiries. Material designers interact with materials and spread new content through different experiential ways of knowing (Clèries & Rognoli, 2021; Santulli & Rognoli, 2020).

In general, samples are the most spread and effective way to interact with materials and encourage experiential knowledge transfer among designers through their tangibility and immediacy (Barati et al., 2019; Karana et al., 2015; Parisi et al., 2017). However, samples only represent the final stage of a deeper investigation and analysis, especially when dealing with emerging materials and technologies to be implemented in real contexts. In this case, intermediate prototypes may add further insight and perspectives to the resulting outcome, i.e., learning how to handle and process a specific material or highlighting some non-quantifiable aspects to be further investigated, such as expressive-sensorial qualities (Camere et al., 2018; Veelaert et al., 2020). Furthermore, using prototypes at different stages is a valuable practice when directly experiencing new materials, helping acquire new experiential knowledge from hands-on activities and direct experimentation. However, transferring this knowledge to a broader audience of practitioners may be difficult, especially when practical experimentations are not engaging them. To this end, experiential tools may help foster this knowledge transfer, and prototypes potentially support their design and development. As a matter of fact, experiential tools should be seen as new artifacts to be designed, tested, and refined through prototypes, including the interaction between the tool and its potential users. Among those, Materials Libraries represent a good way to foster experiential knowledge transfer linked to materials and manufacturing processes. These collections of physical material samples aim to support designers and practitioners during materials selection by providing a tangible experience with materials, understanding their expressive-sensorial qualities, and transferring part of the experiential knowledge entangled in their materiality (Akın & Pedgley, 2016; Rognoli & Levi, 2004; Wilkes & Miodownik, 2018). However, the contribution of multiple prototyping activities in the design of this knowledge transfer has not been adequately explored, and a definition of the different contributions given by prototypes during the whole process is still missing.

This work investigates the role of physical prototypes in designing new experiential tools to spread the knowledge of emerging materials and technologies, such as Materials Libraries. Two practical case studies dealing with waste-based materials and 3D printing are here outlined to critically reflect on the use of prototypes within the design process of the two Materials Libraries. The first one originates within the Horizon 2020 EU Project FiberEUse and considers recycled glass and carbon fiber composite materials as new resources for materials and applications. The second one is an ongoing work focused on new materials and products from waste-based polymers and biomass within distributed networks and communities. After briefly explaining the methodology, the two case studies are presented by resuming the design and development of the two Materials Libraries, the FiberEUse project Library and the RepMat Library. The contribution given by prototypes in designing new Materials Libraries is then provided, resulting in four different possible uses, as well as different roles in shaping and spreading new experiential knowledge.

Methodology

Reflective practice through prototypes

Reflective practice, or Reflection-in-action, helps in linking theoretical concepts of inquiry to real contexts by using practical experimentations and projects to reflect on new theory (Schön, 1992), using design practice as a way to perform research (Friedman, 2008; Goldkuhl & Sjöström, 2018). In other words, artifacts, exhibitions, or products are intended as practical inquiry tools to conceptualize and build new theoretical knowledge from practice (Reich, 2017). Considering the design field, prototyping is one of the most common ways to explore new concepts from the practical context and translate them into theoretical knowledge (Horváth, 2016; Mäkelä, 2007). Prototypes are approximations of artifacts, features, and concepts aiming to refine, communicate, explore, and learn new contents, i.e., products, services, or even knowledge (Camburn et al., 2017; Mäkelä, 2007). From a certain point of view, prototypes are also seen as a tangible result of design experimentations, extending their use in research contexts (Brandt & Binder, 2007).

For the sake of this work, prototypes may assume a double interpretation as methods of inquiry: as an experiential knowledge transfer or a medium to conceptualize theoretical knowledge. The former aspect is discussed within the following sections, and its investigation falls under the objectives of this work. The latter one represents the approach used to understand the role of prototypes in the experiential knowledge transfer or Materials Libraries. In particular, the two case studies described hereinafter represent some situational design inquiries directly performed by the authors. These inquiries allowed us to theorize the role of prototypes through post-evaluation analysis, using the two cases as practical sources for abstraction (Goldkuhl & Sjöström, 2018). This evaluation was performed after the development of the two Materials Libraries, resuming the main steps for the development of the tool itself and the use of prototypes in each phase. The prototypes used during the experimentation were collected and classified according to the main development steps of the two Materials Libraries, better explained in the next section. These prototypes were then analyzed according to: their objectives; their way of use, i.e., to refine the contents or the structure of the library; and their refinement, for instance, preliminary, intermediate, or advanced conceptualization of some parts of the tool. The main contribution of prototypes within this process was then outlined by mapping these differences.

Experimenting with materials from waste for 3D printing

As mentioned, artifacts play a key role in design research and practice, acting as inquiry tools to build new theoretical and experiential knowledge. They may be seen as possible outcomes of design experimentations, which, in turn, are meant as ways to frame new knowledge through making (Brandt & Binder, 2007; Mäkelä, 2007; Niedderer, 2007). This practical approach in design research has been previously exploited to investigate emerging materials, as well as new technologies and digital fabrication (Bauer, 2019; Karana et al., 2015), entangling them with complex socio-technical aspects such as sustainability (Clèries & Rognoli, 2021). As a result, these experimentations aim not only to develop new materials or emerging technologies but also to build tacit and experiential knowledge during the whole process, as well as to foster their transfer to design practitioners (Dew & Rosner, 2019; Santulli & Rognoli, 2020). From the literature, designers are not always aware of these new possibilities for their work. Hence, new ways to foster the knowledge related to emerging materials and technologies are currently required in the next few years (Romani et al., 2021).

The two case studies analyzed in this work are practical experimentations on developing two different Materials Libraries. Their goal is to spread emerging materials and technologies, i.e., materials from waste for 3D printing, for their implementation in real contexts. The main phases of the two case studies are resumed in Figure 1. These steps also correspond to the process followed for building the two Materials Libraries, representing a possible design process for this kind of experiential tool. In detail, the practical experimentations linked to the libraries were structured as follows: (a) Tinkering with the emerging materials and technology through sampling; (b) Defining a taxonomy to classify the knowledge to showcase; (c) Designing and producing the samples according to the classification; (d) designing and developing the structure of the Materials Library; (e) testing the knowledge transfer of the tool, and (f) releasing the new Materials Library.

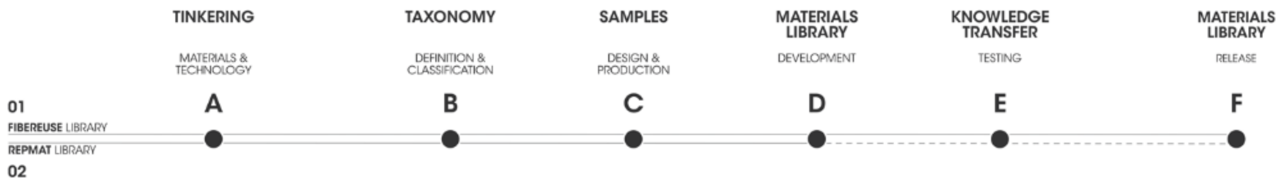


Figure 1: Phases of the practical experimentations from the two case studies: (a) Case study 1 (FiberEUse project Library); (b) Case study 2 (RepMat Library).

Materials Libraries case studies

The two selected case studies aim to spread the experiential knowledge of new materials from waste for 3D printing, fostering their use for new products and applications. The former one, FiberEUse project Library, deals with recycled composite materials from industrial products at their End-of-life, such as wind turbine blades. The latter one, RepMat Library, is a work-in-progress project of an open-source replicable Materials Library for new 3D printable materials from waste-based polymers and biomasses. The case studies were selected for their practical approach to experiencing materials and 3D printing, avoiding those experimentations that focused on designing new applications through prototypes. Indeed, their focus is on developing new experiential tools, in this case, Materials Libraries, because the main goal is to frame the role of prototypes in building and spreading new experiential knowledge.

In short, the two case studies are both focused on Materials Libraries containing new materials from waste for 3D printing. For this reason, the selected process parameters are similar, resulting in similar sample categories. The same taxonomic model was mainly used, and the second case study represents the refinement of the taxonomy used in the first one. Similarly, the second case study can be considered a step ahead in terms of possible uses of the materials library, introducing the concept of replication and structured hands-on activities. To this end, the concept of guided practical experimentations emerged after the development of the FiberEUse project Library as a possible implementation of the experiential tool.

Consequently, the second case study considered this aspect during the development of the second library.

FiberEUse project Library: Materials and Product Library System

The first case study comes from the Horizon 2020 EU Project FiberEUse. It mainly focused on recycling and reusing glass and carbon fibers from waste, especially from products at their end-of-life, i.e., wind turbine blades, construction structures, and technical components from aerospace. The project aimed to integrate new solutions based on recycling and reuse, developing new materials and products by linking research and practical contexts, i.e., industrial partners and designers.

This project resulted in several exploitations dealing with emerging materials and technologies within different application fields, i.e., furniture, sport, and automotive. To better spread their knowledge and foster new practical collaborations, a Materials Library has been designed to include all the solutions from the project. In detail, the original concept of materials libraries has been reconsidered, defining a new experiential tool that includes a physical and virtual experience with materials and products (Romani et al., 2022). This tool, a "materials and product library system," aims to collect materials samples and new products, applications, and other non-textual content. The system comprises two parts: the Physical Library, focused on tangible use, and the Virtual Library, linked to the virtual fruition. Flat samples, product cut-offs, photos, renderings, and technical data can be used and experienced throughout the whole design process, making more accessible the knowledge related to these emerging materials and technologies. After a demo showcased at Milan Design Week 2021, the system has been released for consulting. The physical part is freely accessible on request, whereas the website (anonymized website) includes the virtual part.

This case study mainly considers the Physical Library, which is divided into two parts: the Physical Materials Library (Fig. 2a) with flat material samples and the Physical Product Library (Fig. 2b). This last part represents the focus of the experiential knowledge transfer thanks to physical cut-offs or parts of the main products developed during FiberEUse. The taxonomy of the Physical Product Library was designed to create different three-dimensional structures, one for each combination of material and manufacturing technology, where each sample is defined with a coordinate system and a position. This four-variable spatial taxonomy allows linking a set of variables, i.e., finishing, shape complexity, and process parameters, to a specific spatial position, facilitating comparisons and assessment amongst different parts (Romani et al., 2022).

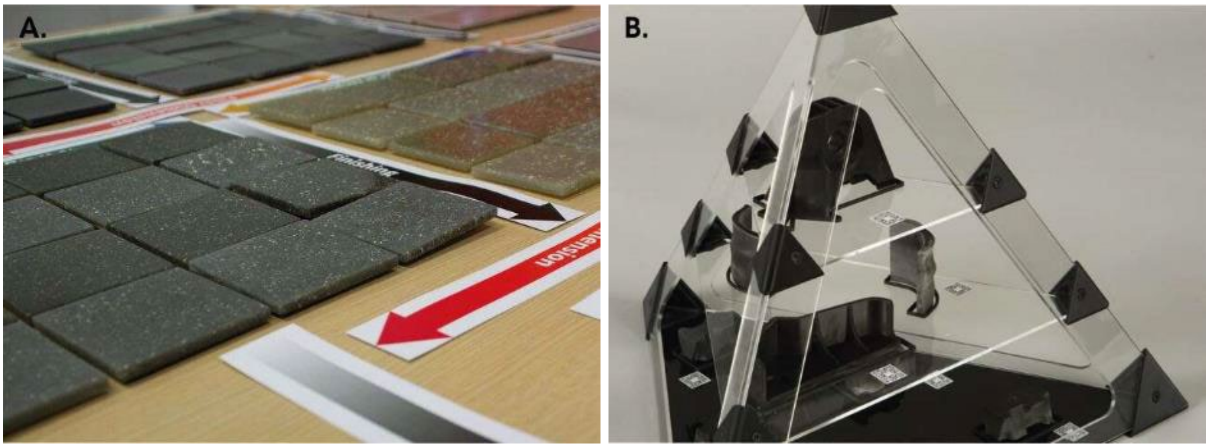


Figure 2: Insight of the Physical Library (Materials and Product Library System) from FiberEUse project: (a) flat samples from the Physical Materials Library; (b) one of the tetrahedral structures of the Physical Product Library.

RepMat Library: Open Source Materials Library System

The second case study is part of RepMat (Replicating Materials Library), an ongoing work focused on new materials, applications, and strategies to implement new circular practices starting from waste-based polymers and biomass. This project originates from the collaboration with local partners, i.e., design studios and maker spaces, aiming to understand the interaction with emerging materials and technologies within the distributed networks of local communities from the Maker culture (Camburn & Wood, 2018; Haldrup et al., 2018; Rayna & Striukova, 2021).

The project's name, RepMat, is explicitly inspired by the RepRap project (Replicating Rapid prototyper: https://reprap.org/wiki/RepRap), the first project aiming to develop a self-replicable Open-Source low-cost 3D printer in 2005. As for the previous case study, this project explores different applications, i.e., furniture, sport, and healthcare. The experimentations have focused on polymer waste from industrial processes and post-consumer goods, i.e., 3D printed scraps, and biomass from the agro-industrial sector, such as hemp hurd. Considering the framework of this project, a more accessible Materials Library is being developed to allow the free use and replication of the system amongst distributed networks of local communities, such as makerspaces. The previous concept of "materials and product library system" has been modified to define an open source system to be freely replicated, modified, and even improved by the users, allowing *distributed* collaborations. Also in this case, the tool will collect different physical and virtual contents, sharing local experimentations and good practices in a distributed virtual environment. This system will be freely released, as well as the materials to allow its replication.

The organizational structure is comparable to the FiberEUse project Library described in the previous sub-section, although its use is meant to give more freedom to the user. In this case, the generative path of the library structure is part of the knowledge transfer that the users can experience through RepMat since it encourages them to directly tinker and experiment with emerging materials and technologies. The Physical Materials Library (Fig. 3a) and the Physical Product Library (Fig. 3b) are therefore meant as practical experimentations rather than just collections of samples. The RepMat Library uses the same taxonomy as the FiberEUse project Library and encourages the user to interact with it by choosing the possible variables to be compared.

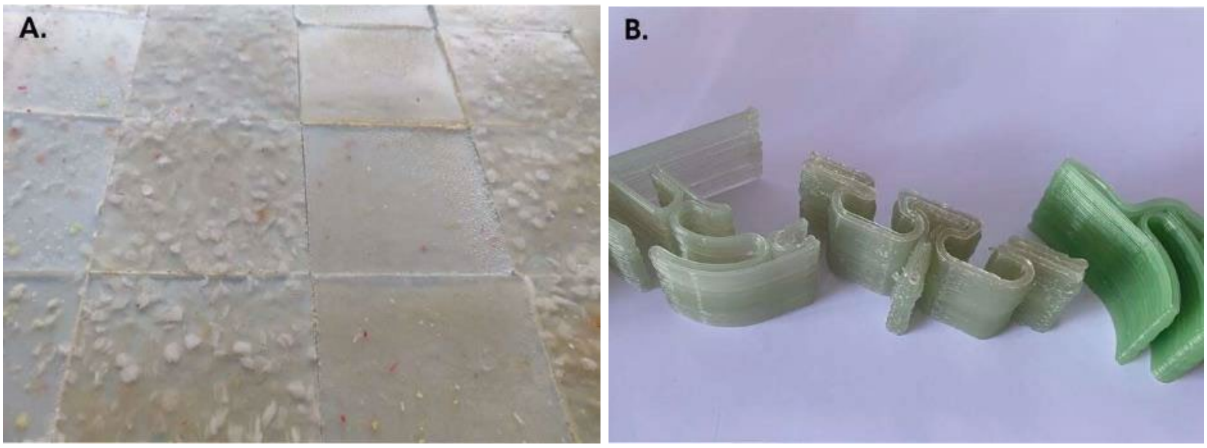


Figure 3: Insights from the open source Materials Library system of RepMat: (a) flat samples from the Physical Materials Library; (b) some physical 3D printed product cut-offs of the Physical Product Library.

Prototypes and experiential knowledge

According to the analysis of the different prototypes used during the development of the two libraries, prototypes may assume different meanings and functions in designing knowledge transfer, especially when dealing with experiential knowledge and new tools. Depending on the phase of the design process of the library (Fig. 1), prototypes can give different contributions in shaping their structure, interactions, and uses. As shown in Fig.4, four different roles of prototypes are outlined in the following sub-sections, thanks to the analysis of the prototypes used in the two case studies. In detail, prototyping helps in: (i) generating and detecting the experiential knowledge; (ii) categorizing and defining the taxonomy; (iii) testing the experiential knowledge transfer; and (iv) speculating on new ways of using Materials Libraries.

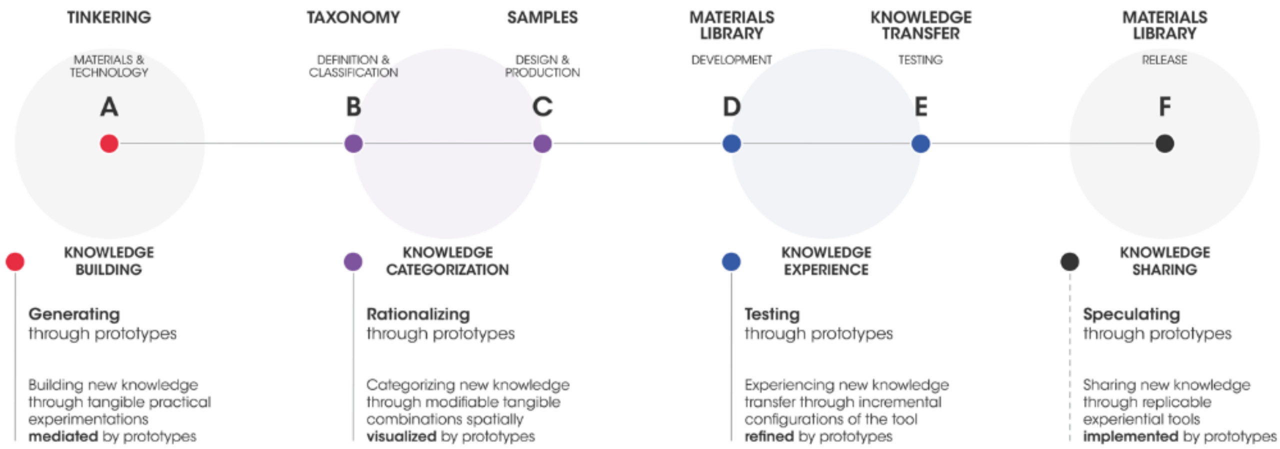


Figure 4: Contribution of prototyping in developing new Materials Libraries and their experiential knowledge transfer linked to the specific development phases.

Generating and detecting the experiential knowledge

The first step in developing a Materials Library aims to understand and select which knowledge should be transferred through the new tool. For emerging materials and technologies, it also means beginning the generative path to give them concreteness. At this starting point, tinkering with the materials and technology allows building this experiential knowledge through practical experimentations, directly experiencing them in the physical world (Fig. 4, Phase A).

Prototypes are, therefore, explorative media that usually do not even appear in the final version of the Materials Library, as for the two case studies (Fig. 5). They aim to progressively define the kind of knowledge to be transferred, encouraging re-iterations during the experimentation. This means trying different material formulations and tuning the processing parameters, both in a structured or non-structured way. Prototypes can represent failures and good results, as both options help understand what needs further investigation. They also contribute to making tangible the tacit knowledge behind these experimentations, including unexpected results from the setup. During this process, the researcher also intertwines their learning process as the first-person actor of the experimentation. This aspect includes dealing with first practical problems and troubleshooting and is strictly linked to the skills of the user behind the experimentation, showing similarities with the concept of digital craftsmanship. Experiencing this crafting path with materials and technology helps detect the tacit contents to be considered during the design process of a Materials Library.

Prototypes contribute to building new knowledge (knowledge building) at this stage. They make tangible these first experimentations, including the troubles, successes, and intermediate results of the iterative tinkering activity. They support knowledge building through tangible experimentations, acting as physical and concrete mediators of this iterative process.

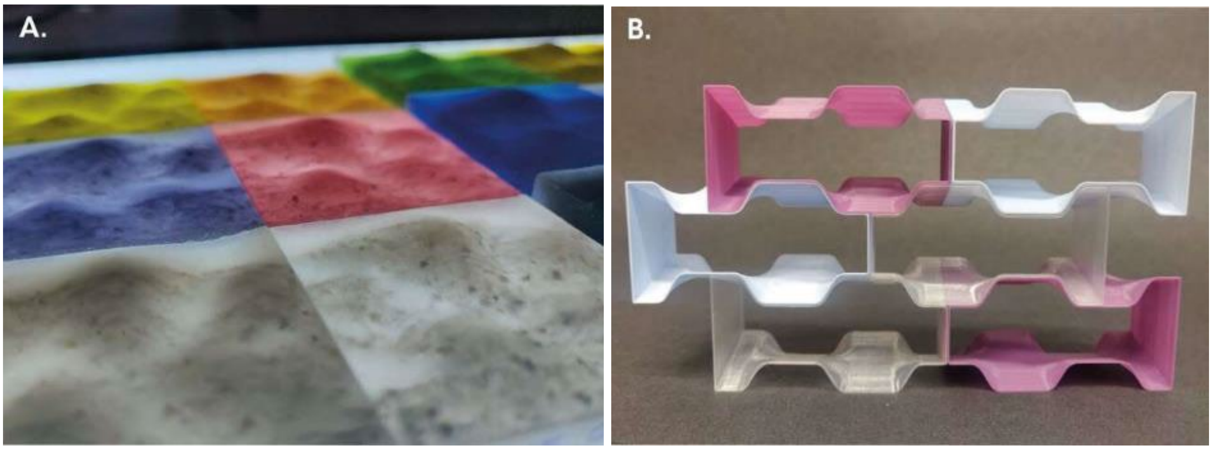


Figure 5: Preliminary prototypes during the tinkering phase with materials and technologies: (a) FiberEUse project Library and (b) RepMat Library case studies.

Categorizing and defining the taxonomy

The second step implies rationalizing and organizing the knowledge to be transferred through the new Materials Library. In this case, the selected knowledge should be categorized according to some meaningful criteria, leading to the definition of a taxonomy before designing the physical structure (Fig. 4, Phases B and C).

Prototypes are used to define possible classifications by combining them in multiple ways, following different criteria for the organization of experiential knowledge. This second approach in prototyping leads to producing some intermediate prototypes or even the final samples showcased in the Materials Library (Fig. 6). They aim to help find some classification criteria by interacting with them. The samples are directly experienced to assess their non-quantifiable aspects, i.e., expressive-sensorial qualities. They can also be used to design and try different taxonomies creating spatial structures to be replicated in the structure of the Materials Library, i.e., matrixes of samples. These interactions help in finding the criteria of the taxonomy and trying to rationalize their fruition. In this case, the different alternatives should be tracked to compare them and select the one that better matches the objectives of the new Materials Library. The researcher can use the experience from the previous tinkering phase to foresee some possible taxonomies, which would be validated or not by producing the prototypes. Experiencing this rationalizing path allows us to organize the tacit contents to be transferred with a Materials Library.

Prototypes contribute to this step in organizing new knowledge (*knowledge categorization*). Prototypes make tangible the classification criteria in the physical world. They help in categorizing new knowledge through modifiable tangible combinations by spatially visualizing the taxonomy.

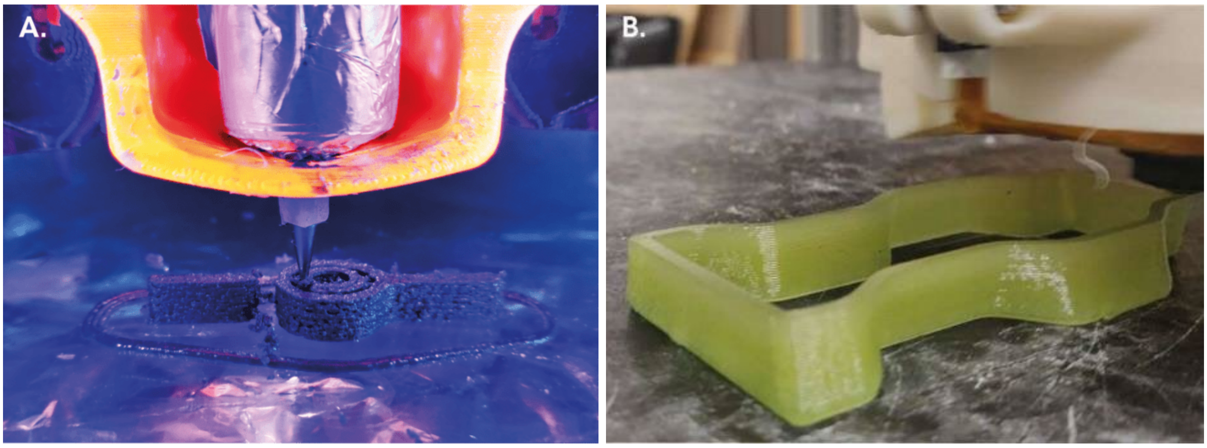


Figure 6: Fabrication of some intermediate prototypes to categorize the materials and process parameters: (a) FiberEUse project Library and (b) RepMat Library case studies.

Testing the experiential knowledge transfer

The third step focuses on designing the library's structure and its use to transfer new knowledge, influencing the experience of potential users with the samples. Developing and testing the physical configuration of the tool also means defining the interactions between the users and the contents (Fig. 4, Phases D and E).

Prototypes help in defining the final layout of the experiential tool. On the one hand, they can be details for testing a specific aspect of the Materials Library, i.e., the fruition of a specific textual or non-textual content. On the other hand, they may be rough versions of the whole product, aiming to refine it by testing it in the real world (Fig. 7). Their goal is to refine the Materials Library by considering it as a product to be developed and tested as in the design practice and industrial contexts. Hence, their use is strictly linked to the assessment and test of the provisional configurations of the library, improving the layout until reaching the final design. Tests may lead to a better understanding of how experiential knowledge is transferred, and iterations help refine this crucial aspect, especially by involving users in this path. The previous tinkering and categorizing experience of the researcher contributes to assessing the usability of the tool, making changes to improve the learning experience, and re-iterating tests. Experiencing this testing path improves the fruition of tacit content and knowledge transfer.

Within this step, prototypes contribute to refining the way to experience new knowledge (*knowledge experience*). They help test plausible interactions designed during the development of the Materials Library by trying and validating them. In addition, prototypes help in experiencing knowledge transfer through incremental configurations of the tool, refining its final design.

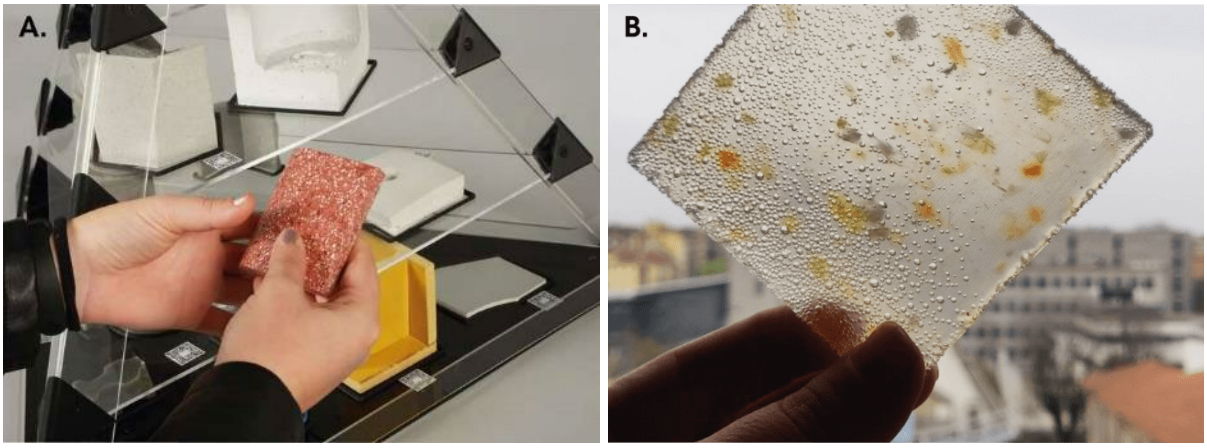


Figure 7: First prototypes of the Materials Libraries and their fruition to evaluate the knowledge transfer and user interaction: (a) FiberEUse project Library and (b) RepMat Library case studies.

Speculating on new ways of using Materials Libraries

A further step may be considered in developing new Materials Libraries, especially after the second case study. When dealing with emerging materials and technologies, the release of the library means starting a continuous process of modification and redefinition of the tool itself, according to the adaptive nature of the topic. This perspective leads to possible speculative reflections on different aspects, such as implementing new materials, technologies, and applications or envisioning new possible ways of developing and using the tool (Fig. 4, Phase F).

The final design of the tool can be seen not only as a prototype to be further refined and updated but even a *provotype*, a provocative prototype, to encourage participative work and hands-on activities (Boer & Donovan, 2012). As a *provotype,* the RepMat Library may foster critical reflections and collaborative ideation, engaging the users in a wider experiential path. The free replication of the library in distributed networks of local communities encourages the users to participate in knowledge sharing and democratizing experimental activities. Users can experience the creation of a Materials Library by replicating its structure and prototypes, trying a deeper kind of experiential knowledge transfer through practical engagement. Meanwhile, users are also participating in a collaborative process of knowledge building, making their experimentations with emerging materials and technologies tangible, generating new experiential knowledge to be shared and added. Experiencing this speculative path fosters the development of new tacit contents to be shared and new engaging paths in transferring experiential knowledge.

Finally, prototypes contribute to sharing new knowledge and speculative reflections (*knowledge sharing*), provoking new experimentations and replications. They help share new knowledge through replicable experiential tools, implementing and modifying them through distributed collaboration.

Conclusions

This work focused on the role of physical prototypes in designing new Materials Libraries to foster the experiential knowledge transfer linked to emerging materials and technologies. The different contributions of prototypes throughout the design process were investigated using a reflective practice approach on two selected practical case studies, the FiberEUse project Library and the RepMat Library.

Four different roles of prototypes were defined through this analysis. Prototyping contributes to (i) generating and detecting the experiential knowledge to be transferred through iterative tinkering activities (*knowledge building*); (ii) categorizing and defining the taxonomy of the Materials Library through spatial visualizations (*knowledge categorization*); (iii) testing the experiential knowledge transfer through concrete interactions in the real world (*knowledge experience*); and (iv) speculating on new possible ways of developing and using Materials Libraries through collaborative *glocal* actions (*knowledge sharing*).

Additional practical case studies should be considered to investigate further prototypes' roles in transferring new experiential knowledge. The analysis should also be performed by widening the perspective and considering different experiential tools, contexts, and users, i.e., non-designers. Nevertheless, prototypes represent a meaningful physical learning medium to tinker with materials or refine the configuration of the Materials Library and to conceive new ways of using these tools, fostering *glocal* collaborations to spread and build new experiential knowledge.

Acknowledgments

The development of the materials Library was funded by the European Union’s Horizon 2020 research project FiberEUse “Large Scale Demonstration of New Circular Economy Value-chains based on the Reuse of End-of-life reinforced Composites” (GA. 730323-1).

References

Akın, F., & Pedgley, O. (2016). Sample libraries to expedite materials experience for design: A survey of global provision. Materials & Design, 90, 1207–1217. https://doi.org/10.1016/j.matdes.2015.04.045

Barati, B., Karana, E., & Hekkert, P. (2019). Prototyping Materials Experience: Towards a Shared Understanding of Underdeveloped Smart Material Composites. International Journal of Design, 13(2), 19.

Bauer, D. B. (2019). Touchable Speculation: Crafting Critical Discourse with 3D Printing, Maker Practices, and Hypermapping. Hyperrhiz: New Media Cultures, 19. https://doi.org/10.20415/hyp/019.e03

Boer, L., & Donovan, J. (2012). Provotypes for participatory innovation. Proceedings of the Designing Interactive Systems Conference, 388–397. https://doi.org/10.1145/2317956.2318014

Brandt, E., & Binder, T. (2007). Experimental design research: Genealogy—Intervention—Argument. International Association of Societies of Design Research, 18.

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2017). Design prototyping methods: State of the art in strategies, techniques, and guidelines. Design Science, 3, e13. https://doi.org/10.1017/dsj.2017.10

Camburn, B., & Wood, K. (2018). Principles of maker and DIY fabrication: Enabling design prototypes at low cost. Design Studies, 58, 63–88. https://doi.org/10.1016/j.destud.2018.04.002

Camere, S., Schifferstein, H. N. J., & Bordegoni, M. (2018). From Abstract to Tangible: Supporting the Materialization of Experiential Visions with the Experience Map. International Journal of Design, 12(2), 51–73.

Clèries, L., & Rognoli, V. (2021). Materials Designers: A New Design Discipline. In Material Designers—Boosting talent towards circular economies (pp. 43–47).

Dew, K. N., & Rosner, D. K. (2019). Designing with Waste: A Situated Inquiry into the Material Excess of Making. Proceedings of the 2019 on Designing Interactive Systems Conference, 1307–1319. https://doi.org/10.1145/3322276.3322320

Friedman, K. (2008). Research into, by and for design. Journal of Visual Art Practice, 7(2), 153–160. https://doi.org/10.1386/jvap.7.2.153_1

Goldkuhl, G., & Sjöström, J. (2018). Design Science in the Field: Practice Design Research. In S. Chatterjee, K. Dutta, & R. P. Sundarraj (Eds.), Designing for a Digital and Globalized World (pp. 67–81). Springer International Publishing. https://doi.org/10.1007/978-3-319-91800-6_5

Groth, C., Pevere, M., Niinimäki, K., & Kääriäinen, P. (2020). Conditions for experiential knowledge exchange in collaborative research across the sciences and creative practice. CoDesign, 16(4), 328–344. https://doi.org/10.1080/15710882.2020.1821713

Haldrup, M., Hobye, M., & Padfield, N. (2018). The bizarre bazaar: FabLabs as hybrid hubs. CoDesign, 14(4), 329–344. https://doi.org/10.1080/15710882.2017.1378684

Horváth, I. (2016). Theory Building in Experimental Design Research. In P. Cash, T. Stanković, & M. Štorga (Eds.), Experimental Design Research (pp. 209–231). Springer International Publishing. https://doi.org/10.1007/978-3-319-33781-4_12

Karana, E., Barati, B., & Rognoli, V. (2015). Material Driven Design (MDD): A method to design for material experiences. International Journal of Design, 9(2), 20.

Mäkelä, M. (2007). Knowing Through Making: The Role of the Artefact in Practice-led Research. Knowledge, Technology & Policy, 20(3), 157–163. https://doi.org/10.1007/s12130-007-9028-2

Niedderer, K. (2007). Mapping the meaning of knowledge in design research. Design Research Quarterly, 2(2), 4–13.

Nimkulrat, N. (2021). Experiential craft: Knowing through analog and digital materials experience—ScienceDirect. In O. Pedgley, V. Rognoli, & E. Karana (Eds.), Materials Experience 2 (pp. 53–66). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-819244-3.00026-0

Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. The Design Journal, 20(sup1), S1167–S1184. https://doi.org/10.1080/14606925.2017.1353059

Rayna, T., & Striukova, L. (2021). Fostering skills for the 21st century: The role of Fab labs and makerspaces. Technological Forecasting and Social Change, 164, 120391. https://doi.org/10.1016/j.techfore.2020.120391

Reich, Y. (2017). The principle of reflexive practice. Design Science, 3, e4. https://doi.org/10.1017/dsj.2017.3

Rognoli, V., & Levi, M. (2004). Emotions in Design through Materials: An Expressive-Sensorial Atlas as a Project Tool for Design of Materials. Fourth International Conference on Design & Emotion, 13.

Romani, A., Prestini, F., Suriano, R., & Levi, M. (2022). Material Library System for Circular Economy: Tangible-Intangible Interaction for Recycled Composite Materials. In M. Colledani & S. Turri (Eds.), Systemic Circular Economy Solutions for Fiber Reinforced Composites (pp. 363–384). Springer International Publishing. https://doi.org/10.1007/978-3-031-22352-5_18

Romani, A., Rognoli, V., & Levi, M. (2021). Design, Materials, and Extrusion-Based Additive Manufacturing in Circular Economy Contexts: From Waste to New Products. Sustainability, 13(13), Article 13. https://doi.org/10.3390/su13137269

Santulli, C., & Rognoli, V. (2020). Material tinkering for design education on waste upcycling. Design and Technology Education: An International Journal, 25(2), 50–73.

Schön, D. A. (1992). Design as a Reflective Conversation with the Situation. In The Reflective Practitioner. Routledge.

Veelaert, L., Du Bois, E., Moons, I., & Karana, E. (2020). Experiential characterization of materials in product design: A literature review. Materials & Design, 190, 108543. https://doi.org/10.1016/j.matdes.2020.108543

Wilkes, S. E., & Miodownik, M. A. (2018). Materials library collections as tools for *interdisciplinary research. Interdisciplinary Science Reviews, 43(1), 3–23. https://doi.org/10.1080/03080188.2018.1435450*

Alessia Romani

Alessia Romani (MSc in Design & Engineering) is a Ph.D. candidate in Design at the Design Department (Politecnico di Milano, Italy), and she currently works as a Research Fellow at the Department of Chemistry, Materials, and Chemical Engineering “Giulio Natta” of the same university. She is currently a visiting PhD candidate at FAST lab, Department of Electrical and Computer Engineering of Western University (London, Ontario, Canada).
Alessia is part of +LAB, the 3D printing lab of Politecnico di Milano, and Materials Design for Transition Lab. Her main research interests focus on the interdisciplinary connection between Design, Materials, and Additive Manufacturing. Alessia aims at bridging design and engineering through the lenses of materials and digital technologies. She is also interested in design strategies and approaches to additive manufacturing (i.e., Open Source); new materials, finishing, and expressive-sensorial qualities for design and additive manufacturing; parametric and computational design; design for sustainability and circular economy.

Valentina Rognoli

Associate Professor in the Design Department at the School of Design, Politecnico di Milano. Here, she studied and began her academic carrier focused on Materials for Design. She has been a pioneer in this field, starting almost twenty years ago and establishing an internationally recognized expertise in research and education. For her Ph.D., she undertook a unique and innovative study on a key but a little-treated topic: the expressive-sensorial dimension of materials of Design and their experiential aspects.
At present, her research and teaching activities are focusing on pioneering and challenging topics such as Materials for Ecological transition; DIY-Materials; Bio-based and biofabricated Materials; Materials from Waste; Materials for interactions and IoT (ICS Materials); Speculative Materials; Tinkering with materials, Materials Driven Design method, CMF design, emerging Materials Experiences, and material education in the field of Design. She is one of the founders of Materials Experience Lab (2015).

Marinella Levi

Marinella Levi received the M.Sc. degree in chemical engineering and the Ph.D. degree in materials engineering from Politecnico di Milano in 1986 and 1989, respectively. Since 2000, she has been the Coordinator of the Laboratory of Chemistry and Characterization of Innovative Polymers. In 2013, she founded +LAB, the first 3D printing laboratory at Politecnico di Milano. She is currently a Full Professor of Material Science and Technology at the Department of Chemistry, Material and Chemical Engineering, Politecnico di Milano. Her current research topics are the design, synthesis, and characterization of advanced polymers and composites for additive manufacturing, electronics, and sustainable materials.

New Textile Transmissions: Reviving traditional textile crafts through replication, unlearning and prototyping

Wang, Yuxi {Leona}, Auckland University of Technology, New Zealand
Cleveland, Donna, RMIT International University Vietnam
Joseph, Frances, Auckland University of Technology, New Zealand

Abstract

Heritage arts and crafts are vital to a nation as they are an artistic expression of its cultural connotations as well as a reflection of its historical development. They are visual communication tools utilised to present and sustain the cultural characteristics and artistic traditions of a particular region. Many of these skills, however, are on the verge of extinction. According to the research published by the Heritage Craft Association [HCA] in May 2021, the total number of 'endangered' crafts increased to seventy-four, along with an additional twenty new 'critically endangered' crafts added between March 2019 and May 2021. Finding solutions or strategies to slow down the pace of extinction has become increasingly critical for all heritage crafts.

This paper considers some of the contextual and methodological issues of a practice-based doctoral research project that focuses on modern technologies and the endangered textile crafts and the culture associated with minority ethnic groups in China. The main objective of this research is to add a new dimension to traditional crafts by integrating new technologies such as electronic textiles to rejuvenate them. This paper explores the translation of aspects of traditional crafts into contemporary textiles through processes of replicating and prototyping. This strategy, based on the communication of textile knowledge is distinct from other approaches such as the use of handcraft techniques in haute couture or luxury product lines, it seeks to revitalise crafts by employing an unlearning process and acknowledging experiential knowledge through iterative, hands-on textile prototyping processes to create more contemporary modes of textile expression, rather than product applications.

A selection of prototypes, including experiments with traditional weaving and embroidery techniques, as well as the use of these techniques in developing e-textile experiments, will be discussed. This practice-driven research encourages creative risk-taking, happy accidents, and improvisation by experimenting with traditional stitch structures, ancient and new yarns and unfamiliar e-textile components and processes. This paper reflects on diverse prototyping processes and shares insights from a collaborative process with experts from various disciplines. It explores how modern technologies, contemporary materials, and traditional handicraft processes can be cohesively combined to produce interactive e-textile narratives through material understanding and making processes.

Heritage crafts, Experiential knowledge, Prototyping, Unlearning, Interactive e-textile, Narratives

Global production systems and the digital revolution have accelerated the abandonment of many practices including traditional craft and their associated skills, artifacts, and tools. Heritage crafts have served important purposes to societies and individuals in the past. They were the objects in which we stored memories, commemorated significant life events, or demonstrated identities. However, people continue to seek aesthetic gratification, community and meaning. This paper explores ways culture and memories can be embodied as narrative into new interactive textiles, offering additional meaning, relevance and value to the textiles. To achieve this, a process of learning and replicating was initiated. This included sourcing textile samples, copying, practicing and experimenting with traditional embroidery and weaving techniques from books or online. The project has also involved experimentation with a wide range of conductive materials and consultation with multidisciplinary experts. The processes and methods of prototyping and un-learning (Marr & Hoyes, 2016) have contributed to the development of new perspectives, a broadening of cross-disciplinary and cross-cultural understandings, and an exploration and focusing of a design research topic.

Background

Daniel Carpenter of the Heritage Crafts Association (HCA) notes that the disappearance of heritage crafts is not only a loss of beautifully handmade objects but also the stories behind each craft and the tradition that once helped shape the people and history (Carpenter in Madden, 2020). A sizable percentage of the world's population are living a faster-paced, life of mass consumption while the value and sense of satisfaction in taking time to create has diminished in importance. While awareness of heritage crafts has been better promoted in recent years, and governments are also working on strategies to create economic value by utilising such intangible heritage (Yang, Shafi, Song, & Yang, 2018), the enormous impact that colonisation, industrialisation and globalisation has brought to traditional cultures and their handicrafts has been immeasurable. The rapid development of new production technologies has further accelerated the demise of heritage crafts. Prior to industrialisation, most products were handcrafted by artisans in small workshops or at home. Expertise for each technique was accumulated through generations. Artisans spent years honing their skills before passing them on to descendants. This cycle is being discontinued as descendants loose interest in continuing the tradition, or cannot make a living doing so (HCA, 2017). As existing artisans become older and without successors, we lose more of our past and cultural heritage.

The research documented in this paper engages with traditional textile crafts of minority Ethnic groups in Southern China. Their location in remote areas and localised economies, has meant the clothing culture of Chinese ethnic minorities has been well preserved as they were less affected by mainstream society and external cultures. Most of these ethnic minorities didn't have writing systems or existing characters suitable for their own languages. In order to preserve their own history without written records, messages were embedded into their textiles along with the method of 'jiang gu' (verbally transmitted legends), as a dual assurance to pass on customs or knowledge to descendants. These messages or memories turned their costumes into carriers of traditional culture (Shijie, 2018).

Several examples that demonstrate this aspect were identified in this study, namely heritage textiles from the ethnic minority groups known as the Miao and Yao. The Lanjuan dress from the Miao, an indigenous group living in the south and southwest areas of China, is a skirt decorated with migration pattern in the Guizhou area and white lantern pants from Baiku Yao, demonstrate how storytelling has been used in the context of minority cultures. Legend suggests that Lan Juan was a female leader and heroine of the 'Miao' group. For the purpose of escaping advanced enemies, she led her compatriots to the south. In order to record the journey of the southward migration, Lan Juan created a method of utilising-coloured threads to mark different landmarks they encountered along the way on her clothes. For example, when they departed from the Yellow River, Lan Juan sewed a line of yellow thread on her left sleeve; when crossing the Yangtze River, she embroidered a blue thread on her right sleeve; when crossing the Dongting Lake, she embroidered a lake-like pattern on her chest. Since then, every time Lan Juan crossed a river or mountain, she would record the experience on her dress. At the end of the journey, her dress was covered with densely embroidered intricate patterns from neckline to the hem. According to the marks Lan Juan remembered, she later created an exquisite wedding dress with a variety of different coloured threads and meaningful symbols for her daughter. This wedding dress is named after her and has become a lasting memorial of the remarkable leader. Nowadays, the wedding dress for a traditional bride is similarly decorated as the ancient Lanjaun dress which is a way of honoring the heritage (Ronghui, 2007). Minority groups in China used craft techniques to record ethnic culture and to journal history.

The diminishing standing of traditional crafts illustrates the need for more research in this field, to discover viable methods to bring new vitality to this heritage. This paper discusses work in progress presented through prototypes, including embroidery and weaving samples. By revisiting traditional textiles and surface embellishment techniques, the replication method focuses on learning and identifying aspects of the tradition that can be carried forward into the present. The prototyping method aims to examine potential ways of incorporating new elements into traditional approaches. An unlearning strategy (Marr & Hoyes, 2016) is employed to assist the researcher to engage more with the prototyping processes rather than a set-end product. It highlights the discovery of new perspectives and happy accidents by embracing uncertainty and encouraging creative risk-taking during the prototyping process.

Methodology

Replication

Replication is a method of reproducing an item, technique, or knowledge by employing tools, materials and conditions that are sufficiently identical (Peels, 2019). It is also a procedure to validate findings by repeating the same process (Plucker & Makel, 2021). By combining customary knowledge and practical experience, it is also a valuable technique used in fields like archaeology to recover or recreate long-lost techniques or textiles (McKendry, 2019).

Replication, in this research, is a strategy used to assist the researcher in understanding techniques and, above all, in establishing a connection with the past. The process of copying and replicating these processes connects the researcher/maker to a time when craft skills were needed for survival and textiles were both a significant investment of human labour and a piece of precious memory. This learning by-doing and making approach is acknowledged and promoted by craft educators (Niranen, 2021).

The Un-learning Strategy

Replication and continuity are critical to the practice and sustainability of traditional craft. They have been vital not only in understanding technique, but in understanding deeper cultural contexts and values. Processes of replication were the first step in understanding and practicing traditional craft techniques. However, in order to develop new potentials and awareness of these traditional crafts, the project needed to move beyond replication. The concept of unlearning (Salustri & Rogers) was introduced as a way to go beyond the habitual:

> Once we have learned to do something in a certain way, we will tend to do that thing the same way forever, or until a 'better' way presents itself (and sometimes, not even then). In this way, we will tend to not try other ways to do a thing because we have learned one way of doing it (2008, p. 7).

This research employs a risk-taking approach by merging an open-ended, process-led research method with an 'unlearning' strategy of consciously exploring material boundaries and experimenting beyond the unknown. 'Unlearning' is a course of action which offers opportunity to acquire new perspectives and create new hybrid practices through 'un-learning' established parameters and laying existing assumption aside (Marr & Hoyes, 2016). It concentrates on the actual process rather than a preconceived outcome. Due to the uncertain and risky nature of this method, the end results of each research cycle could be valuable setbacks, happy accidents or total failure and shift in direction (Marr & Hoyes, 2016). By embracing uncertainty, the researcher was encouraged to engage more with process rather than preconceived or expected end results. This hands-on experiential learning process enables the researcher to identify intricate knowledge and acquire new perspectives through textile experimentation.

Toiles as Prototypes

A sample is a product which represents a group or batch of products, in order to assess their quality, style or design (Sayed, n.d.). A textile sample is a piece of fabric designed to demonstrate a larger whole. In this project sampling is used as a design strategy in conjunction with replication as methods of prototyping. In fashion design, a garment sample is commonly known as a toile, and the process of making the sample is referred to as toiling (Tokens, 2020). The term prototype is used in various industries, such as product design, and engineering design. The production of samples and toiles in fashion and textile design are also forms of prototyping.

Prototyping is a design process of creating multiple artefacts in order to swiftly test or develop ideas before the final product is manufactured (McElroy, 2017). This method can be used at various stages of the design process. In the early concept stage, it can be used as a tool to experiment or explore ideas (concept prototypes); or to identify problems or refine ideas at later development stages (proof of concept prototypes); it can also be employed to communicate and sell a product to a client at the final stage (working prototypes). Depending on the project requirement, prototypes can be constructed at various scales, in two or three dimensions, and with low or high fidelity (Valentine, 2013).

This research has employed the term sample or sampling method for any two-dimensional textile prototypes created in the early stage of the project to eliminating terminological ambiguity. Samples in the form of smart garments (toile) or e-textile experiments are referred to as prototypes.

Prototyping methods are employed in conjunction with an action research framework throughout this research. The process unfolds in iterative cycles of making, testing, and reflecting. Making is the process of transforming ideas into tangible form. Testing is a crucial step to determine the future scenario of use. Reflection takes place throughout the process (reflection in action) and is also an important final step to consider and critique the viability of the prototype (reflection on action), (Schon, 2006).

E-textiles

Textiles have surrounded people across different cultures and historical periods. Most traditional textile narratives are expressed through motif, but textile expression also uses sensory or embodied experience to enhance or perform aspects of the narrative. Through vision, touch or gesture, textiles can be used to evoke emotions or memories.

E-textiles is an emerging field that allows electronic components like batteries, lights, sensors, and microcontrollers to be embedded in textiles. E-textiles are included in various-categories such as wearables and smart clothes. They are incorporated into forms such as garments, accessories or furnishings to provide additional functionality such as sensing analysing, and transmitting relevant and appropriate information, services and resources (Seneviratne, 2020). They are often integral to the wearer.

Beyond functional applications, e-textiles are also being explored as an artistic medium or form of communication. Examples include: The Interactive Pillow project (Enervi, Redstrom, Redstrom and Worbin, 2005), which consists of two pillows, each in a different location, that are designed to connect and light up when one of them is hugged. The 3D Printed Conductive Sequins project (Ma and Yamaoka, 2022) is inspired by the traditional craft of sequin embroidery. When a force, such touch or press, is applied to the sequins, the circuit generates a signal that is sent to a computer. They also function as motion sensors, responding to body movement and posture detection. These projects have brought valuable insights to this research because they have used prototyping processes to develop interactive textiles that react or respond to human engagement to enhance textile communication.

An important material associated with e-textiles is conductive thread. It is often made from silver or stainless-steel fibre and utilised for sewing or weaving connections between electronic components. Copper tape and tin sheet, seen in traditional ethnic Chinese textiles, were used in initial replicated samples. However, their conductive properties were identified during later prototype stages, and both were used as alternative conductive materials. Metallic threads and metal beads were also explored in combination with conductive threads and traditional materials. A list of e-textile materials is included here to explain the components used during the prototyping process.

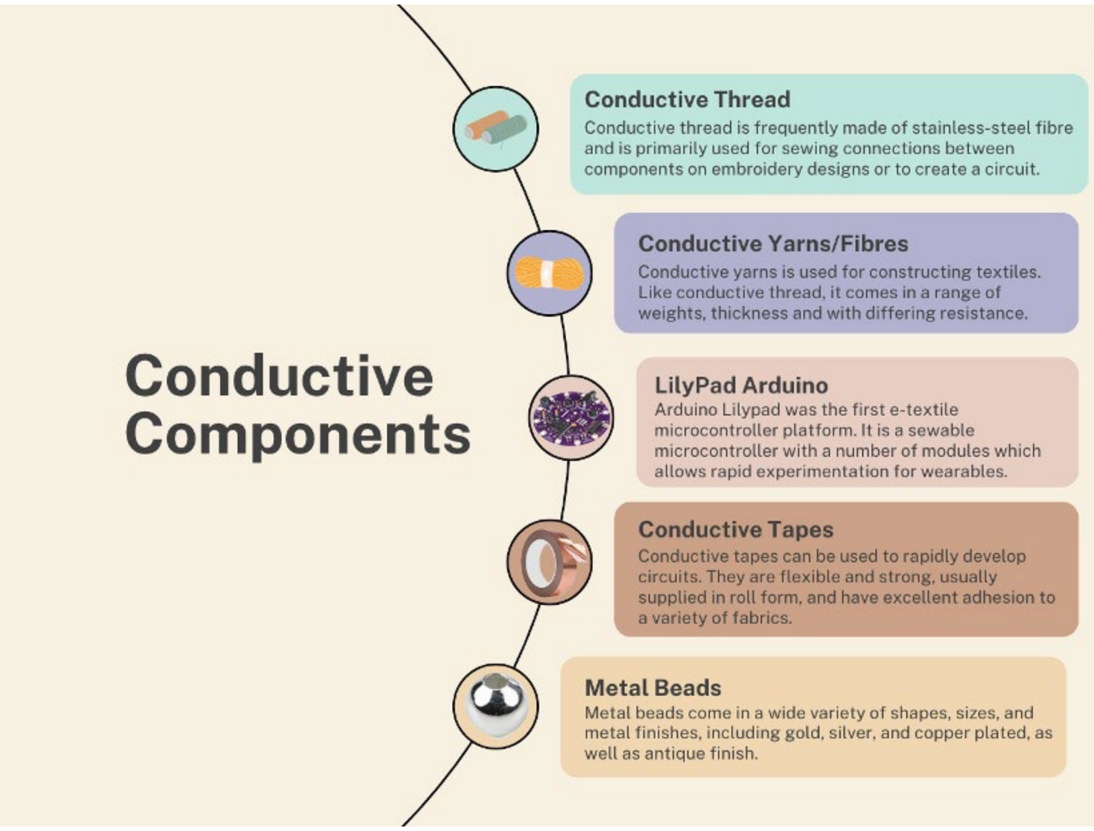


Figure 1: Wang, L. (2022). Conductive components

The structure or pattern of a textile also played a significant part in the prototyping process as it affects the behavior and thus the electronic characteristics of a textile. Before starting the actual making process, consideration and planning must be given to where electronic components can best be placed and ensuring that the positive and negative traces do not cross over at any point. In terms of weaving, different types of conductive yarns and patterns were tested first in order to understand the behaviors and electronic characteristics of the textile.

Textiles are highly expressive materials that can elicit emotions or memories through vision and touch (Davis, 2017). Creating interfaces for people to capture or receive information in ways that engage other senses can be culturally embedded in textiles (Davis, 2019). Initial experiments revealed the possibility of textile expression through technique by utilising traditional techniques and the inherent expressive ability of textiles in combination with new materials and the interactive potential of e-textiles. This project explores new possibilities for traditional craft through making, with an emphasis on interactive and story-telling textiles.

Traditional Techniques

Embroidery and weaving are ancient arts that span many cultures. A key distinction between these textile methods is that weaving produces a textile, allowing for the inclusion of different materials within the fabric construction, while embroidery is like a form of applique that is attached to a textile's surface. The following overview of two traditional techniques - tin embroidery and weaving/embroidery combined stitching – introduces forms that were identified through the making process of this research as having potential for e-textile application. This potential is linked to the materials used and the spatial configuration of the yarn in or on the textile.

Tin Embroidery

Tin embroidery is a technique of the Miao people which uses the metal ‘tin’ as an additional ‘thread’ in their complex embroidery patterns, utilising both regular embroidery threads and tin strips. The normal threads form a stitched foundation on the cloth, and tin is then applied as a unique type of decorative technique on top of a stitched pattern to emphasise the main design and also add a rich gloss to the textile (figure 2).

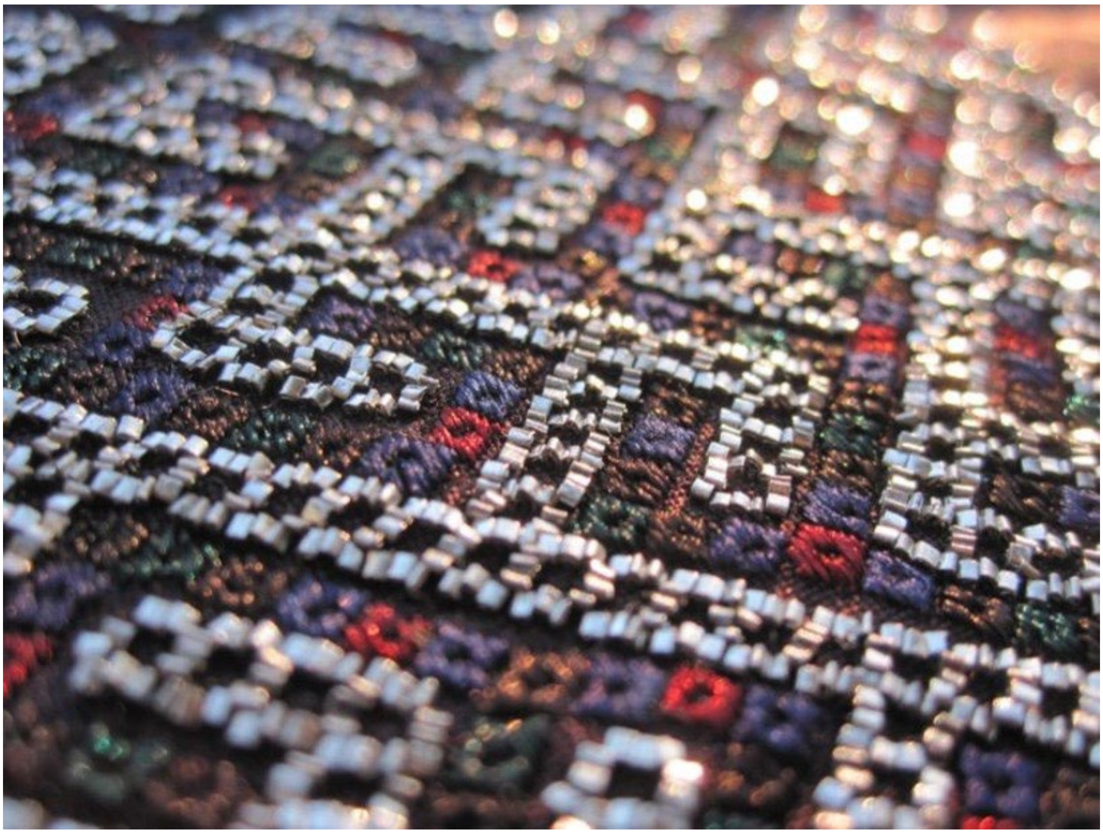


Figure 2: Banfudehuajiushu. (2016). Tin embroidery

The embroidery patterns used by the Miao people originated from and have been passed down using paper cutting techniques. However, artisans from Liufu Miao in Guizhou province of China recorded their pattern in a different way where each family had their own master pattern moulds, also known as ‘mother patterns’ (Ying, 2016). This is an indispensable tool for younger generations to learn the skill which has always been regarded as a family heirloom passed on from generation to generation, normally between mother and daughter or daughter-in-law.

In addition, the Miao people believe silver holds special social and cultural connotations. It is closely associated with the religious martial arts and historical migration of the Miao people (Ying, 2016). For the Miao people in Jianhe, costumes made using tin embroidery were a symbolic, non-verbal way of recording and communicating their own unique social and historical situation and a tool to define their identity, taste and temperament. Liufu Miao utilises these special embroidery patterns as the main carrier to generate and express specific meaning in different circumstances. These symbols can be decoded by locals using their own rules.

Figure 3: Banfudehuajiushu. (2016). Embroidery creation by a Miao artisan

Weaving and Embroidery Combined Stitching

Two forms of weaving and embroidery combined stitching were of particular interest. The first type applies needlework on top of a semi-finished patterned handwoven fabric, comparable to modern cross stitching. When experienced artisans weave the base pattern into the cloth, they attempt to replicate the texture of the embroidery to make the combination look more seamless.

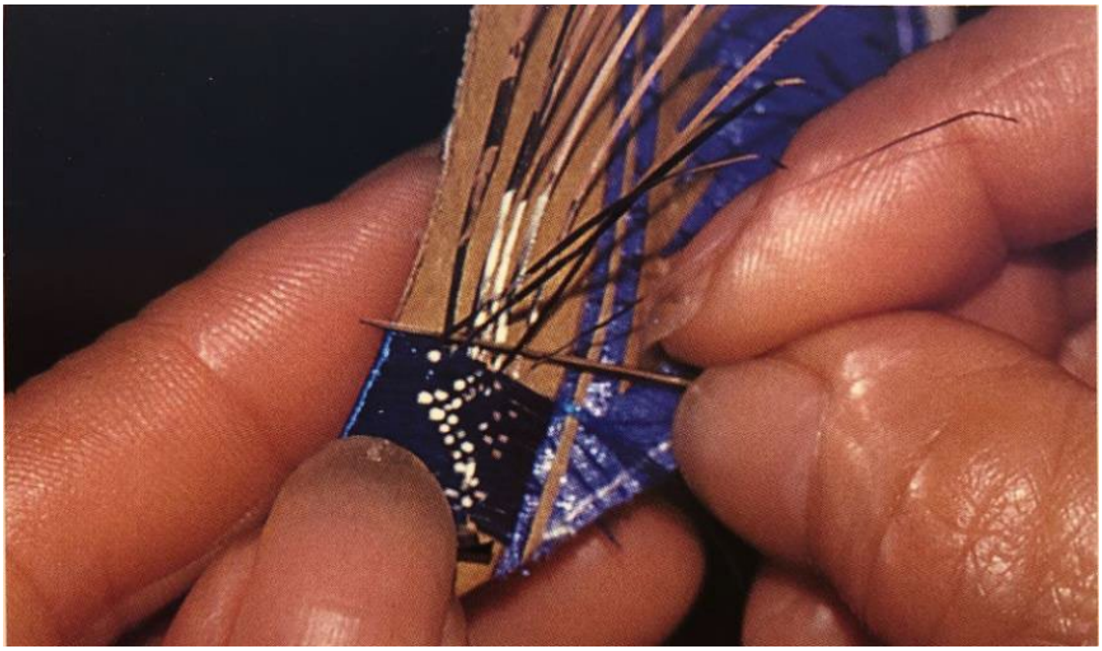


Figure 4: Torimaru, T. (2018). One Needle, One Thread

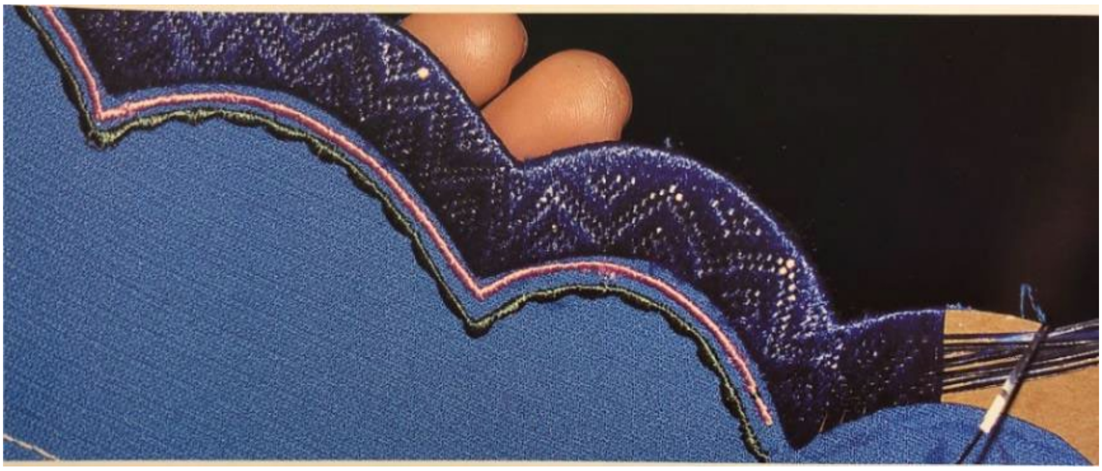


Figure 5: Torimaru, T. (2018). One Needle, One Thread

The second form of weaving and embroidery combined stitching uses strings of embroidery thread or strips of tinfoil as warp, another group of embroidery threads as weft and the needle as the shuttle (Torimaru, 2018). The artisan must first set up and secure the warp threads before using the needle to shuttle through them to create the pattern based on the chosen design. The process of weaving is cleverly combined with embroidery in this technique and the resulting textile is extremely detailed and intricate (figures 4 and 5). This is a hand-held weaving technique that is impossible to produce with a traditional handloom. Miao artisans make significant use of this technique with tinfoil as binding fabric to decorate the raw edges of their costumes.

Both types of weaving and embroidery combined stitching, along with tin embroidery are methods that are further explored in this research. Reviewing these processes enabled a deeper understanding of the fundamentals and theory of the stitching, which aided subsequent stages of research through the making process.

The Prototyping Process

This section discusses four key stages of the prototyping process – replication, textile exploration, e-textile prototyping and reflection (figure 6). It begins with the initial process of learning and practicing selected techniques, then progresses to a series of experiments with different machinery, modern materials and embroidery/weaving structures. This is followed by the development of e-textile prototypes and concludes with the refection stage to determine the next course of actions.

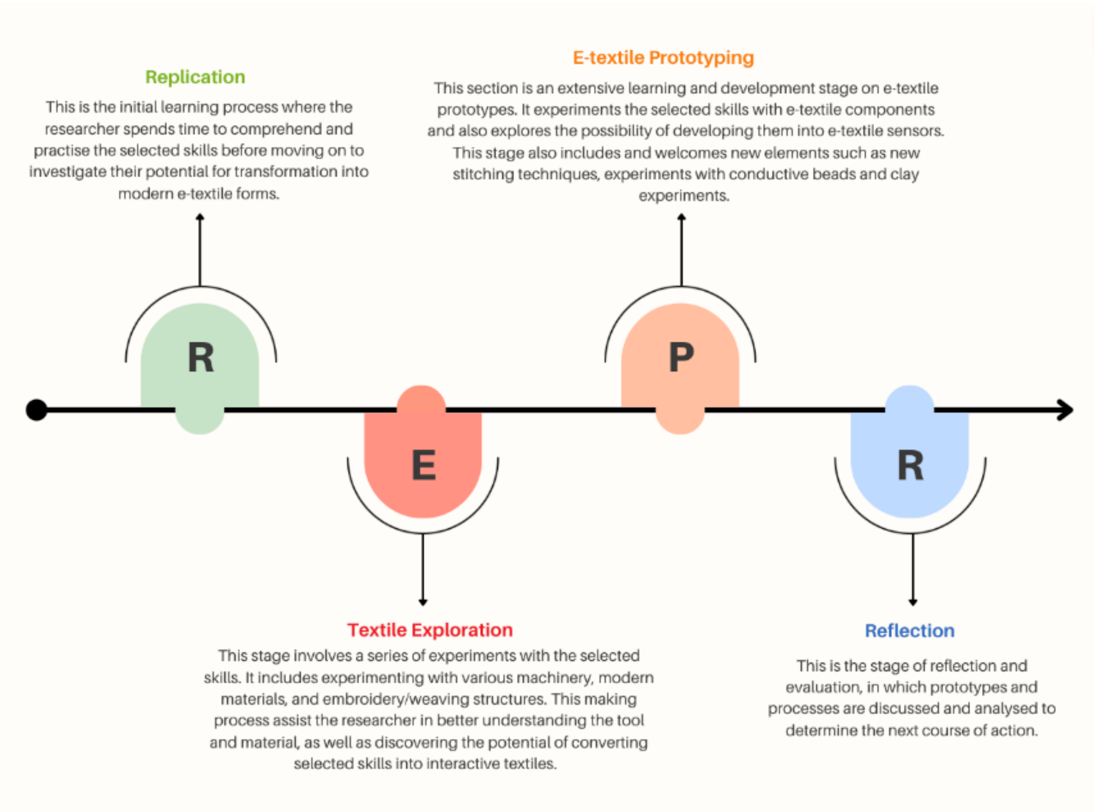


Figure 6: Wang, L. (2022). The prototyping process

Initial Stage – Replication

The replication method has been a crucial part of the research as a learning process to comprehend and practice the selected skills before the project moved to exploring the potential for transformation into modern forms. There are two types of replications used in this project:
1. Re-creating the technique as closely as possible using similar equipment and materials, and
2. Re-creation using modern materials or technologies.

Figures 7 and 8 below show examples of the first type of replication. They are the first set of prototypes created by the researcher using readily available materials to learn technique. It is not a straightforward experience to replicate these traditional skills because there is limited information online or in books to immediately understand the techniques. All the knowledge to replicate the textile comes from a combination of prior experience as well as sourcing online photos and documentary videos. The process of replicating these techniques was not only informative in understanding how the structure functions, but it also provided an appreciation for the significance of material preparation and the amount of practice required to achieve the desired result.

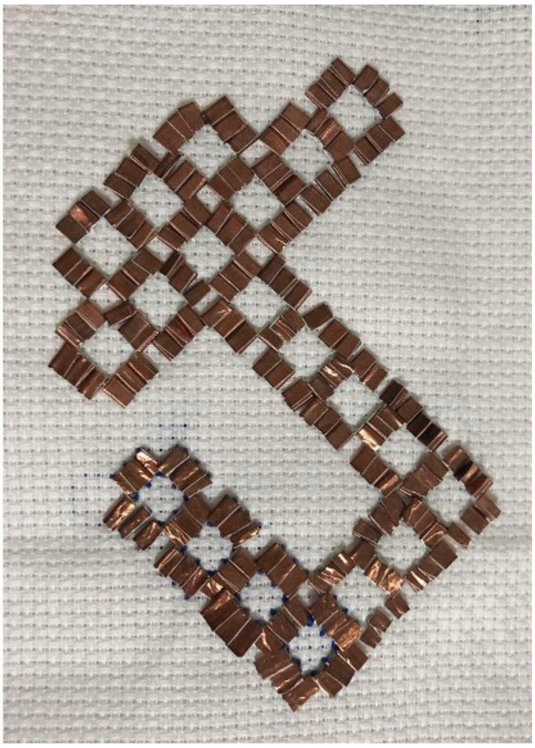



Figure 7: Wang, L. (2021). Traditional Weaving stitching A

Figure 8: Wang, L. (2021). Traditional Tin Embroidery (Based on Miao techniques)

After gaining a basic understanding of the skills, samples were developed employing modern machinery and materials. The sample in figure 9, shows first attempts using a more contemporary approach towards traditional weaving/stitching. Experimentation with the same method using a continuous conductive copper strip on a TC2 digital weaving loom involved several different weaving structures. These included plain weave, basket weave, and twill weave. Figure 10 shows an experiment involving a more complex weaving stitch structure using conductive threads. Since conductivity is a crucial component of smart textiles, new embroidery structures were first prototyped by hand before transferring them to the digital loom to save time and material and build knowledge through processes of making. Having embroidered and woven multiple samples, with many mistakes, a more nuanced understanding of both traditional skills and e-textiles was gained. These experiences and insights contributed greatly to the next phases of the research.

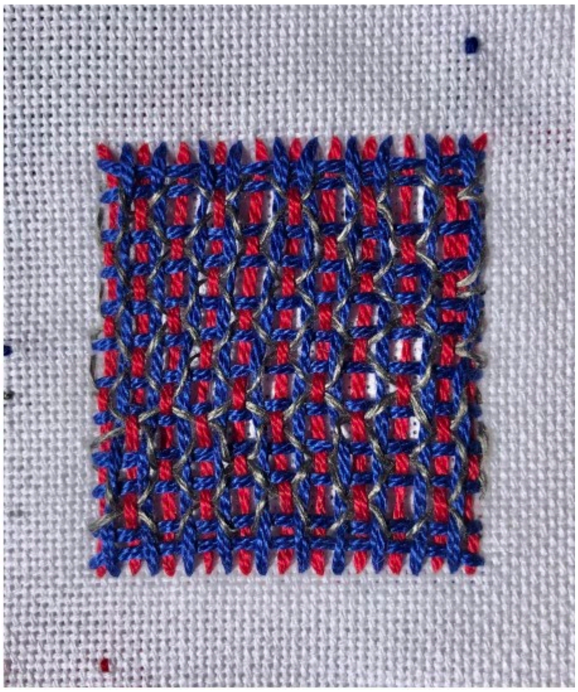


Figure 9: Wang, L. (2021). Weaving TC2 Loom Sample A

Figure 10: Wang, L. (2021). Experiment with weaving stitching K

Textile Exploration – Weaving

Figure 11: Wang, L. (2022). Experiment on a desk loom

After the initial replication and learning processes, a series of woven samples were produced to test out different machinery (figure 11), yarns and weaving structures. Samples were made using ultraviolet (UV) reactive colour-changing yarn, temperature-sensitive colour-changing yarn, glow in the dark yarn and a variety of conductive yarns (figure 12-15). The procedure was intended to assist the researcher in better understanding the materials and tools and to explore the potential of converting them into interactive textiles through the making process.


Figure 12: Wang, L. (2021). Weaving TC2 Loom Sample B (Left) – conductive yarn with twill weave

Figure 13: Wang, L. (2021). Weaving TC2 Loom Sample C (Right) – conductive yarn with satin, twill and satin weaves

Conductive yarns and fibers are available in a variety of textures, hardness's and conductivity levels. In general, conductive yarns are frequently made with conductivities that range from 5Ω/m to several kΩ/m (Gottlieb, 2015). To achieve the best electrical properties, they are produced entirely or partially of metallic fibres with stainless steel being the most commonly used material (Tong, 2018). The simplest approach to incorporate these yarns into a fabric is to weave them as a warp or a weft, however, they are generally not insulated (Turner, Salleo, & Parlak, 2020). Project Jacquard by Google's Advanced Technologies and Products team (ATAP), which incorporates electronics into garments by weaving with conductive yarns and threads (Guler, Gannon, & Sicchio, 2016) is a relevant example using such techniques.

Different types of conductive yarns were used in combination with various weaving structures to test out potentials. The stiffer outcomes feel more metallic and less like fabric which made them ideal for shaping. Soft choices were considerably easier to work with and the result resembled more traditional fabric.

The possibility of weaving cultural motifs using conductive yarn was also explored. Figure 16 shows some delicate flower patterns from southern minority groups in China. These flower patterns are subtle because the yarn used is very thin and the weaving pattern is not dense enough. A variety of weaving patterns, including diamond weave, twill weave, and plain weave, were tested using UV reactive colour-changing yarn, temperature-sensitive colour-changing yarn, and glow in the dark yarn. Challenges, such as, the need for optimal density of the patterns for some yarns to react, the activating temperatures for temperature-sensitive colour-changing yarn, and the necessity of charging glow in the dark yarn during the day, were all valuable discoveries to bring to the next round of prototyping.


Figure 14: Wang, L. (2021). Weaving TC2 Loom Sample E (Left) – UV reactive colour-changing yarn, temperature-sensitive colour-changing yarn and glow in the dark yarn

Figure 15: Wang, L. (2021). Weaving TC2 Loom Sample F (Right) – Dimond weave; UV reactive colour-changing yarn, temperature-sensitive colour-changing yarn and glow in the dark yarn

Figure 16: Wang, L. (2021). Weaving TC2 Loom Sample G – Flower motif (from the southward minority groups in China) with conductive yarn

Textile Exploration - Embroidery

Embroidery is another technique that was explored extensively in this project. Major areas of investigation included traditional embroidery techniques, motifs and an analysis of the material and mechanical behavior of specific stitches. Initially, a series of embroidery samples were created. The aim of these experiments was to test various weaving stitching combinations in order to better understand the structure of the embroidery and how it might be used with electronic materials and components. The exploration of different thread options or combinations was another objective of this sampling process. The hands-on creation process allowed for the acquisition of further experience and understanding.

Weaving stitching was the first embroidery technique learnt during this process. Figures 17 and 18 are interpretations of three-dimensional weaving stitching. These were new concepts that emerged from studying the traditional weaving stitch. Experimentation also involved the use of different types of modern embroidery threads while employing traditional stitching structures (figures 19-20). Although working with conductive thread is not difficult, the threads can become twisted and tangled together very easily, therefore it is crucial to maintain a short thread strand. Metallic embroidery threads are extremely challenging to work with. While they have the same feel as working with genuine metal threads, they don't remain in the anticipated position. Glow in the dark, UV reactive colour changing, and temperature sensitive colour-changing threads perform similarly to metallic threads. Making elaborate patterns using these threads can be very difficult. Through these experiments it was discovered that ambient temperature has a big impact on temperature sensitive threads and it can be a challenge to maintain the colour.

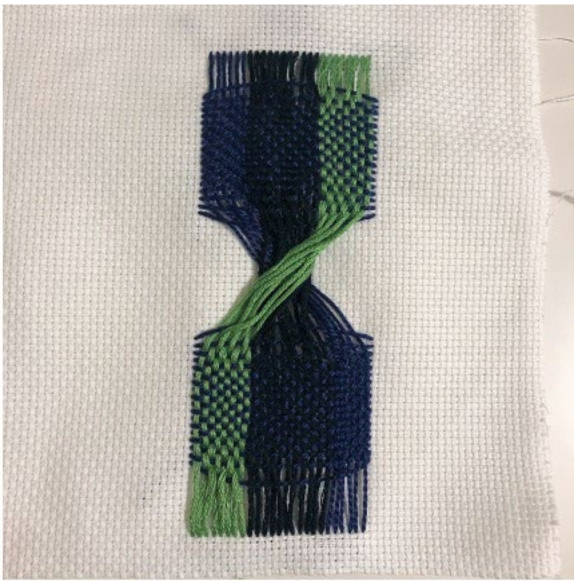



Figure 17: Wang, L. (2021). Experiment on 3D weaving stitching B (Left)

Figure 18: Wang, L. (2021). Experiment on 3D weaving stitching D (Right)

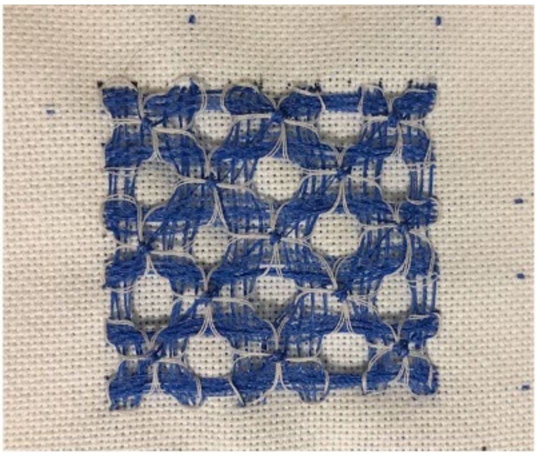



Figure 19: Wang, L. (2021). Experiment on weaving stitching G (Left) – Gold metallic thread

Figure 20: Wang, L. (2021). Experiment on weaving stitching I (Right) - temperature-sensitive colour-changing thread and glow in the dark thread

E-textile Prototyping

Tin embroidery prototype

Prototyping processes were also used to explore the potential of traditional embroidery or weaving techniques to produce e-textile systems. The first prototype drew inspiration from tin embroidery (figure 21). The sample was made up of an LED light, a battery holder, copper strips, conductive thread and regular thread. This prototype relies on decorative copper pieces to establish the electrical connection for the LED circuit. It was anticipated that the LED light would turn on as soon as the battery was inserted; however, it became evident that the copper pieces were not all sitting flat on the fabric, so some of them were not touching each other. Therefore, the circuit only worked when someone interacted with it, for example, by pressing the copper pieces or moving the entire piece (figure 22). This is where the unlearning strategy resulted in a happy accident whereby the circuit disruption caused by the way the copper moved became an opportunity for gestural interaction with the textile to enable the electronic response or expression.

Figure 21: Wang, L. (2021). Tin embroidery prototype with LED

Figure 22: Wang, L. (2021). Tin embroidery prototype with LED

Net Embroidery Stitching Prototype

The second prototype was inspired by net embroidery stitching (figure 23). Net embroidery is a creative and ever-changing stitch. The embroiderer first creates the outline or nets and then fills in the pattern inside each net. The most common net structures for this technique are triangles, diamond shapes and ball shapes. There are numerous variations and combinations available for both the net structure and the design inside the net. For the e-textile prototype sample (figure 24), a triangle structure and snowflake design were used. The grey conductive threads and the normal, bright orange threads are used to secure and separate certain strings of conductive threads to ensure there are no short circuits or crossing threads. The structure of this technique is fascinating; almost as if it was designed specifically for producing e-textiles. For example, the use of gold metal threads and the use of normal thread in the middle of each pattern to separate the metal threads. The use of mathematics in designing the embroidery layout and the limitless combination of patterns could enable the creation of larger, more complex circuitry.

Figure 23: Nian, B. H. (2017). Traditional Net embroidery stitching

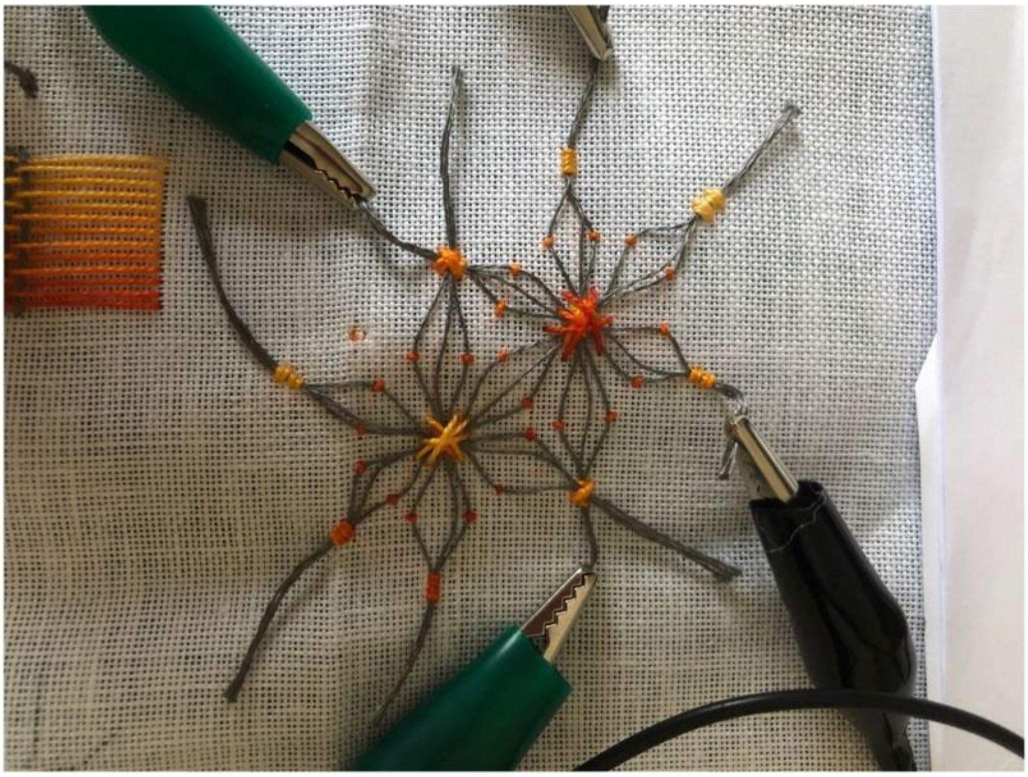


Figure 24: Wang, L. (2022). Net embroidery stitching with conductive threads

Metal Bead Prototypes

The third experiment expended from the tin embroidery prototype, using metal beads, rather than metal strip, to connect the circuits (figure 25). The metal beads are stitched together as closely as possible and secured with seed stitching on the top of the beads. The beads in the centre section were held with regular embroidery thread, while the ones on the sides were made with conductive thread. Because of the shape of the beads, it is challenging to keep them touching or connecting with each other, no matter how closely they are stitched together. This suggested the idea of an interactive embroidery piece that would respond when a force, such as pressing or squeezing, was applied to the beads.

In another prototype using metal beads and conductive yard the conductive thread was used to thread the metal beads and also to make the grey embroidered patches placed next to the beads. The bead loops randomly touch the grey patch on either side as the fabric moves. Figure 27 shows how the top two bead loops touch the left patches while the remaining bead loops touch the right side. This interactive embroidery prototype produces a variety of combinations that could be used to trigger different e-textile reactions. The potential of using the dynamic movement of the textile to generate this e-textile expression as part of a narrative was noted and will be further explored and extended through application on different garment types and positioning in relation to different parts of the body and associated gestures or dynamic movements.

Figure 25: Wang, L. (2022). Metal beads with seed stitching

Figure 26: Wang, L. (2022). Metal beads prototype four combination one (left)

Figure 27: Wang, L. (2022). Metal beads prototype four combination two (right)

Sensor prototypes

One e-textile prototype was a bead sliding sensor similar to the Danish Krown Slide-Switch (Plusea, n.d.). For this prototype, beads are strung on conductive thread. When the beads touch, the electrical contact between the threads is bridged, thus closing the ‘switch’. The same theory was applied in the creation of more variations. The prototype in the middle of figure 28 activates when beads touch either side of the conductive thread. If they are touching, the ‘switch’ is closed, otherwise, the ‘switch’ is open. The prototype on the right functions the same, when beads come into contact with the conductive threads at an angle, the electrical contact between the threads and beads is bridged. Figure 29 shows a slightly more complex version of the bead sliding sensor. The beads, however, do not slide smoothly due to the texture and placement of the blue threads. Once again, it only functions when someone engages with it. Tin embroidery was used instead of beads in prototype six in figure 30. This option slides more easily than the bead option.

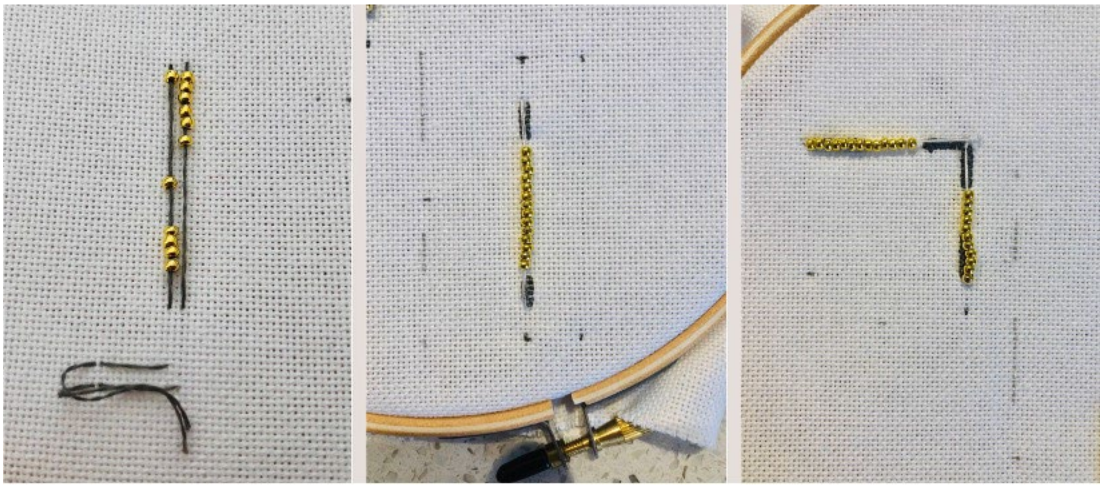


Figure 28: Wang, L. (2022). Metal beads prototype five – slide sensor

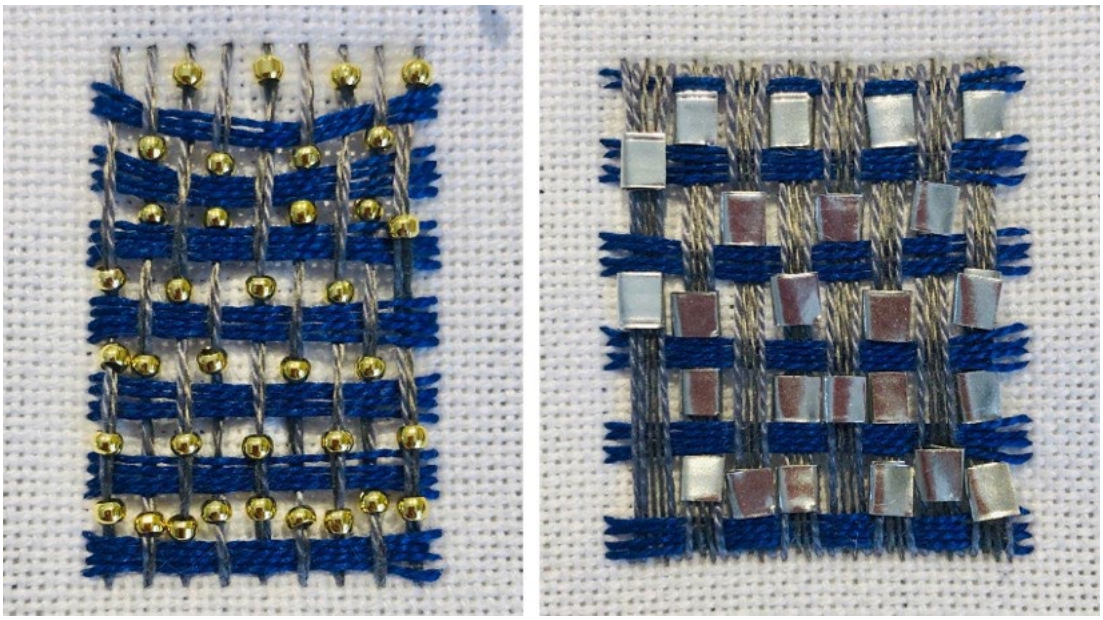


Figure 29: Wang, L. (2022). Metal beads prototype five – slide sensor (Left)

Figure 30: Wang, L. (2022). Tin embroidery prototype six – slide sensor (Right)

The potential of other types of sensors made using traditional techniques was further explored. Figure 31 is a touch sensor made with conductive thread and green embroidery threads. It works like a switch and operates when the grey section is touched. Figure 32 shows a squeeze sensor where weaving stitching has been used to embroider the shell. To achieve a tactile squishiness, the sensor is filled with non-conductive stuffing. It functions similarly to a touch sensor, except the switch can only be activated when squeezed.

Figure 31: Wang, L. (2022). Weaving embroidery – touch sensor

Figure 32: Wang, L. (2022). Weaving embroidery – squeeze sensor

Conclusion

Four primary processes – the replication method, an unlearning strategy, prototyping and narrative through interaction – have informed this project. All four approaches are based on experiential learning through different forms of engagement with materials and processes.

Replication is an approach widely used in the transmission of craft-based knowledge. With limited available information about traditional skills, this method has been used to analyse and reproduce traditional techniques. From an analysis of these samples replicating traditional techniques in combination with the use of new materials, in a prototyping process, new approaches with potential for developing interactive narratives through e-textiles have been identified.

The researcher started this project from a position of interest in e-textiles and the desire to pass on traditional craft knowledge to future generations. A specific form of design output was not established at the beginning of this project. The open-ended nature allowed the researcher to experiment with a range of processes and ideas. An unlearning strategy is critical to this project and was integrated with the prototyping process. By challenging the researcher to think outside the box and experiment with new materials and processes, creative risk-taking was encouraged. Happy accidents and improvisation emerged from this risk taking. This strategy also allowed the researcher to deeply connect to the practice, extending the study in a personal sense. By embracing uncertainty and not having a fixed end product, more possibilities and potential for invention and innovation were opened up (Marr & Hoyes, 2016).

The prototyping process for this project is exploratory. The problem that frames the project is a complex cultural one of the loss of craft and the value of textile narratives. There is no simple solution for this 'wicked' problem (Rittel & Webber, 1973). The experimental prototyping process is about taking risks, putting aside existing assumptions, and exploring the unknown through making.

This paper identifies some techniques and opportunities for producing interactive e-textiles capable of communicating new narratives through a series of prototyping processes using modern technology, contemporary materials and traditional handicraft. The implications of interactive narratives are not fully explored in this paper. The potential of moving beyond visual narrative communicated through symbolism and motif – a strategy used in traditional textile communication – to forms of narrative activation through performative strategies using gesture, movement and tactile engagement – suggest new ways of involving people more intimately and interactively in understanding and appreciating more contemporary textile expressions.

Instead of preserving the crafts in their original form, this research attempts to develop a creative and meaningful blending of the contemporary and the traditional through a making process. This is an ongoing project and the next stage will involve an iterative process of proof-of-concept prototyping - further exploring interactive narrative, drawing inspiration from current prototypes and developing them into smart textile samples or forms. As a practice–based inquiry, the final design outcomes have not yet been determined. It may be presented as garments, or a collection of working prototypes. The final format of the design artefacts will be determined by the behaviour of the textiles, the audience or wearer, and the relationships between textile techniques, materials, and new technologies to enable original forms of textile expression and narrative transmission.

References

Datareportal. (2022). Digital around the world. Retrieved from https://datareportal.com/global-digital-overview#:~:text=A%20total%20of%205.07%20billion,of%20the%20world's%20total%20population.

Davis, F. 2019. FELT: Communicating Emotion Through Textile Expression. Textile Expression, Technology|Architecture + Design, 3:2, 146-149, DOI: 10.1080/24751448.2019.1640524

Davis, F. 2017. "Softbuilt: Computational Textiles and Augmenting Space through Emotion." PhD dissertation, Massachusetts Institute of Technology.

Ernevi, A, Redstrom, M, Redstrom, J, & Worbin, L. (2005). The Interactive Pillows. IT+ Textiles: Boras, Sweden: The Interactive Institute and the Swedish School of Textiles, 47–54.

Gottlieb, S. (2015). Why Apple dumbs down your smartphone. Retrieved from https://www.forbes.com/sites/scottgottlieb/2015/12/04/why-apple-dumbs-down-your-smartphone/?sh=3fd824f33393

Guler, S. D., Gannon, M., & Sicchio, K. (2016). Crafting Wearables. Retrieved from *https://link-springer-com.ezproxy.aut.ac.nz/chapter/10.1007/978-1-4842-1808-2_3*

Lim, Y. (2017). Felted Terrain: Interactive Textile Landscape; Transforming the Experience of Knitted Textile with Computation and Soft Electronics. Retrieved from https://www.intechopen.com/chapters/57095

Liyan, T. (2005, March 1). Research on the tin embroidery of Miao Nationality in Jianhe. Retrieved from https://www.docin.com/p-760060322.html

Madden, H. (2020). From a sea silk seamstress to a goldbeater: meet the master artisans keeping endangered crafts alive. Retrieved from https://robbreport.com/shelter/art-collectibles/last-artisans-keeping-endangered-crafts-alive-2898761/

Ma, H., & Yamaoka, J. (2022). Smart Textile Using 3D Printed Conductive Sequins. Retrieved from https://dl-acm-org.ezproxy.aut.ac.nz/doi/10.1145/3490149.3505577?query=%22Smart%20Textile%20Using%203D%20Printed%20Conductive%20Sequins%22+AND++++2022

Marr, A., & Hoyes, R. (2016). Making Material Knowledge: Process-led Textile Research as an Active Source for Design Innovation. Journal of Textile Design Research and Practice, 4:1, 5-32, DOI: 10.1080/20511787.2016.1255447

McElroy, K. (2017). Prototyping for Designers: Developing the Best Digital and Physical Products. Retrieved from https://ebookcentral.proquest.com/lib/AUT/detail.action?docID=4785196

McKendry, L. (2019). Replication of a Maori Ethnographic Textile Hem Border Pattern. EXARC Journal, 2019 (4), Retrieved from https://exarc.net/issue-2019-4/at/replication-maori-textile

Niiranen, S. (2021). Supporting the development of students' technological understanding in craft and technology education via the learning-by-doing approach. International Journal of Technology and Design Education, 31, 81-93. Retrieved from https://link.springer.com/article/10.1007/s10798-019-09546-0

Peels, R. (2019). Replicability and replication in the humanities. Research Integrity and Peer Review. 4(1), 1-12, Retrieved from https://doaj-org.ezproxy.aut.ac.nz/article/532af2f16f184ae4bc9914a97aa48ebf

Plucker, J. A., & Makel, M. C. (2021). Replication Is Important for Educational Psychology: Recent Developments and Key Issues. Educational Psychologist, 56(2), 90-100, Retrieved from https://eric.ed.gov/?id=EJ1295405

Plusea. (n.d.). Danish Krown Slide-Switch. Retrieved from https://www.kobakant.at/DIY/?p=5053

Rittel, H., & Webber, M. (1973). Dilemmas in a General

Ronghui, W. (2007). Yunxiang Clothes: the spirit of Chinese national costume. Beijing, Peking University Press

Salustri, F., & Rogers, D. (2008). Some Thoughts on Terminology and Discipline in Design. Retrieved from https://dl.designresearchsociety.org/cgi/viewcontent.cgi?article=2129&context=drs-conference-papers

Sayed, M. A. (n.d.). What Is Sample? Types Of Sample. Retrieved from https://textileapex.blogspot.com/2014/10/sample-types.html

Schon, D. A. (2006). The reflective practitioner : how professionals think in action. https://ebookcentral.proquest.com/lib/AUT/detail.action?docID=4816972

Seneviratne, P. (2020). Beginning e-Textile Development: Prototyping e-Textiles with Wearic Smart Textiles Kit and the BBC micro:bit. Retrieved from https://link-springer-com.ezproxy.aut.ac.nz/chapter/10.1007/978-1-4842-6261-0_1

Shijie, Y. (2018). The local scenery of Guangxi. Beijin, Social Sciences Academic Press.

The Heritage Crafts Association [HCA]. (2017). The Radcliffe red list of endangered crafts. Retrieved from http://heritagecrafts.org.uk/wp-content/uploads/2017/04/The-Radcliffe-Red-List-of-Endangered-Crafts-Research-Report-revised.pdf

The Heritage Crafts Association [HCA]. (2021). The Radcliffe red list of endangered crafts. Retrieved from https://heritagecrafts.org.uk/redlist/categories-of-risk/

Theory of Planning. Policy Sciences. 4(2), 155-169. https://www.jstor.org/stable/4531523

Torimaru, T. (2018). One Needle, One Thread. Beijing: China Textile Press.

Tokens, E. (2020). What Is A Toile: Toiles, Muslins and Sample Garments. Retrieved from https://www.thecreativecurator.com/what-is-a-toile/

Tong, R. (2018). Wearable Technology in Medicine and Health Care. London, United Kingdom: Academic Press.

Turner, A.P.F., Salleo, A., & Parlak, O. (2020). Wearable Bioelectronics, Amsterdam, Netherlands: Elsevier.

Valentine, L. (2013). Prototype: Design and Craft in the 21st Century. Retrieved from https://www-bloomsburydesignlibrary-com.ezproxy.aut.ac.nz/encyclopedia?docid=b-9781350036031

Wiseman, R. (2007). Pace of life project. Retrieved from http://www.richardwiseman.com/quirkology/pace_home.htm

Yan, Y., Shafi, M., Song, X., & Yang, R. (2018). Preservation of cultural heritage embodied in traditional crafts in the developing countries. A case study of Pakistani handicraft industry. Sustainability, 10(5), 1336, Retrieved from https://doi.org/10.3390/su10051336

Ying, Z. (2016). Research into the Art Charater and Culture Symbols of Tin Embroidery of Miao Minority in Guizhou Jianhe. Folk Art and Culture, 274274, 112-115. Retrieved from https://www.ixueshu.com/document/392640aa9dc9556a318947a18e7f9386.htm

Shimmering Wood – Design “Thinging” in Material Development Process

Noora Yau, Department of Design, School of Arts, Design and Architecture, Aalto University, FI-00076 Aalto, Finland
Konrad Klockars, Department of Bioproducts and Biosystems, School of Chemical Engineering, Aalto University, FI-00076 Aalto, Finland
Kirsi Niinimäki, Department of Design, School of Arts, Design and Architecture, Aalto University, FI-00076 Aalto, Finland

Abstract

This paper presents an interdisciplinary research project where new material is developed in a collaboration between design and materials science. The objective of the Shimmering Wood project is to develop a nanocellulose-based structural color and investigate its possibilities in the context of design. We present two interconnected design cases that focus on the visual possibilities of the **coffee ring effect**, a feature of nanocellulose-based structural color. The text shows how new knowledge is built through **design "thinging"** – through constructed prototypes, material tinkering, and laboratory experiments.

By analyzing the design "things" we aim to answer these questions:

1. What can interdisciplinary research and iterative knowledge building through design "thinging" look like?
2. How can design "things" be used in the materials’ development process to imagine and envision a new way to use nanocellulose-based structural color?

Prototyping; Structural color; Interdisciplinary research; Nanocellulose; Design

Projects and studies in which design and materials science work together have become more common in recent years (e.g., CHEMARTS in the Aalto University, Materials Experience Lab in the Delft University of Technology, and the Politecnico di Milano). Generally, the motivation for such endeavors arises from the desire to develop new environmentally friendly materials and from the fact that designers and material scientists often look at materials from slightly different perspectives (Niinimäki et al. 2018).

According to Karana et al. (2015), the material development process usually focuses on developing the materials' functional and technical properties. Niinimäki et al. (2018) have also stated that innovations are often born from a science-driven approach. In contrast, the other properties of the materials – e.g., social, cultural, sensory, and emotional – get less attention, even though they play an important role in how new materials are understood and how they succeed commercially (Karana et al. 2015).

Design is often used to create experiences for existing and commercially available materials

(Karana et al. 2015). An emerging way to collaborate between materials science and design is aiming to design experiences in connection to materials already in the development stage. To help us understand and consider all the nuances we experience when interacting with materials, Karana et al. (2008) introduced the concept of *materials experience*, which refers to a comprehensive take on the properties of materials.

The context of design can be useful for considering the material's properties as a whole since physical products can be seen as mediums in which people interact with materials (Karana et al. 2008). Karana et al. (2008) have also noted that the same demands for products apply to materials – in order for products to be desired and appreciated, products (and the materials they are made of) need to arouse emotional experiences as well as fulfill the functional expectations of end users (ibid.).

Implementing design methods such as constructing prototypes in the material development process could open a dialogue about material properties that might be an unconventional topic in basic materials science research. Still, those same unconventional properties might play a central role in forming the identity of materials and creating a meaningful materials experience. Koskinen et al. (2011) state that design deals with things somewhere "halfway between people and things". These "halfways" might be difficult to verbalize, but they are related to feelings, images, thoughts, associations, and connections the products and materials evoke in the experiencer. Because of their difficult-to-measure form, they may not be seen as relevant to serious research topics (Koskinen et al. 2011). However, designers are trained to deal with these "halfways" and imagine what could be; working with materials which do not exist yet (Niinimäki et al. 2018).

Collaboration between design and science can help change perspectives, open new views into materials, and even be "mind-opening", as described by one materials scientist in a study by Groth et al. (2020): "Accepting disciplinary differences might build a more multifaceted picture of our world." Therefore, new undiscovered material properties or new areas of application can be found through interdisciplinary collaboration. Materials have qualities that are difficult to measure and therefore difficult to study with the conventional methods from natural science, but these qualities might be crucial in understanding different materials (for example, what we consider aesthetic, pleasurable, or comfortable).

In their 2008 article *Material Considerations in Product Design: A Survey on Crucial Material Aspects Used by Product Designers*, Karana et al. divided the properties of materials into tangible (measurable properties, such as material strength and weight) and intangible (properties that cannot be measured in the same way). They noted that intangible properties are often not studied and are not included in reports and material manuals in the same way as tangible properties. And yet, those intangible features are crucial for designers in the material selection process of product design (Karana et al. 2008).

As it seems that all the properties of materials are not equally studied and developed in the material development process, an interesting question arises: What if the material's properties were considered more holistically already at the development phase of the material? Our approach to this challenge has been an interdisciplinary collaboration between design and materials science. Design methods have been implemented in materials science by bringing prototyping and **design "thinging"** (a term adopted from Koskinen et al. 2011) into the material development process alongside basic materials research.

Koskinen et al. (2011) discuss design as an act of "thinging". These "things" mean all kinds of models, scenarios, and prototypes that are *"tools for transforming designers' intuitions, hunches, and small discoveries into something that stays – for instance, a prototype, product, or system. They provide the means for sketching, analyzing, and clarifying ideas as well as for mediating ideas and persuading others*". They also argue that these "things" can be used as communication tools between different disciplines.

Design "thinging" – methods such as prototyping, material tinkering, and experimentation – has been at the center of our interdisciplinary project Shimmering Wood since the beginning of the collaboration. These design "things" have provided a medium through which several different properties of materials are examined simultaneously instead of focusing on one feature and its variations. "Thinging" has been our way of imagining and building the possible future of the material, examining its limits and possibilities, and making it visible to third parties and ourselves.

This paper considers the role of design "thinging" in the material development process through the Shimmering Wood project. The project investigates nanocellulose-based structural color and its possibilities in the context of design. We present two interconnected design cases that focus on investigating the visual possibilities of the **coffee ring effect** – a feature of nanocellulose-based structural color. By analyzing laboratory tests, material tinkering, and prototypes, we aim to answer the questions:

4. What can interdisciplinary research and iterative knowledge building through design "thinging" look like?
5. How can design "things" be used in the material development process to imagine and envision a new way to use nanocellulose-based structural color?

Background

Structural color is a color formation mechanism based on the interaction of light and nanosized structures. Nature's examples of structural color include peacock feathers and the wings of *morpho* butterflies (Kinoshita et al. 2008). Biologists and optical physicists have studied these colors and the mechanisms underlying color generation (Kinoshita et al. 2008; Doucet & Meadows 2009; Parker 1995; Burg & Parnell 2018). Lately, these colors' aesthetical and technical properties have also gained more interest in materials science (Zhao et al. 2012; Shang et al. 2019). Although nature is a master at creating these color-producing nanostructures, biomimicry attempts have led to effect color developments that utilize the interaction between nanostructures and light. Usually, however, these colors require plastic or metal-based materials or contain toxic ingredients (Green et al. 2021). The awareness of the harmfulness of different dyes has aroused interest in, for example, the structural color derived from nanocellulose.

Structural Color from Cellulose Nanocrystals

Structural color can be created with cellulose nanocrystals (CNC) (Schütz et al. 2020). They come in the form of aqueous suspensions, where they can self-assemble into a structure that can be preserved by drying the suspension into coatings (Revol et al. 1992). CNCs themselves form transparent materials, but the nanostructure they form selectively reflects a narrow spectrum of light, giving rise to structural colors. There has been extensive scientific interest in CNC-based structural color (Miyagi & Teramoto 2021), but there are still no products that utilize this technology commercially. Research of CNC-based structural color has mostly focused on potential applications in optical devices such as optical sensors (Zhao et al. 2021. Recently, Droguet et al. (2022) explored the potential of manufacturing sustainable effect “pigments” from CNCs in a large scale. In addition to the applications mentioned above, we believe that CNC structural color could have the potential as an environmentally friendly colorant for the design and art field.

The Coffee Ring Effect

As the technical applications of CNC-based structural color have been researched and developed, the visual and aesthetic aspects of this new colorant have received much less attention than the functional and technical ones. CNC-based structural color presents an interesting tension between the technical and aesthetic properties of the material. The nanostructure that forms the color is sensitive to changes in conditions. Changes in the technical properties (for example, increasing the flexibility of the nanocellulose film) may also dim or brighten the color produced by the nanostructure or affect the perceived hue and texture. The slightest change in the recipe can significantly impact the result. Thus, the aesthetic consideration of color cannot be completely separated from the development of the technical properties of the material.

Materials may have properties that seem insignificant for technical applications. However, the same properties may be of great visual importance in design. In our recent work (Klockars et al. 2019), we explored the **coffee ring (CR) effect**, a certain property of structural color from cellulose nanocrystals. In the coffee ring effect (Deegan et al. 1997), the suspension of colloidal particles (in this case, CNCs) dries faster in the edges of a coated area. This leads to a thicker coating at the edges than at the center due to capillary flow of particles toward the edges. The CR effect created with CNCs leads to inhomogeneous color that gradually redshifts towards the edges of the coating (Mu & Gray 2015). For this reason, it has been perceived as a burden in materials science.

The CR effect in CNCs has been traditionally studied using circular coatings (Mu & Gray 2015; Gencer et al. 2017; Gencer et al. 2018) as this leads to homogeneous CRs that are easy to study (Klockars et al. 2019). In this previous work, we suggested using the CR effect as a visual tool to emphasize the shape of logos, forms, and patterns. We studied it in more arbitrarily shaped coatings, which are more often used in actual designs. The CR effect could be discussed as a highlight effect in the design field (Yau et al. 2020).

In this text, we present how we have investigated the behavior and visual possibilities of the CR effect through design "thinging". Compared to the stringent requirements for colors in technical applications (like the previously-mentioned optical devices), the requirements are more relaxed in a decorative context, and the CR effect can be considered a visual element. Since we study coatings of more complex shapes instead of round ones, the term "ring" does not describe the effect well. Therefore, we prefer to refer to the effect as the **coffee rim effect** instead, keeping the acronym CR.

Methodology

Research through Design

This study is a collaborative project between materials science and design with a **Research through Design (RtD)** approach. Materials science practices are part of our research, which we complement with design methods.

Given the iterative and unruly nature of design processes, it is difficult to give general guidelines for how RtD should be implemented (Gaver 2012). However, some methods for combining materials science and design have been suggested, such as Material Driven Design (MDD) by Elvin Karana et al. (2015), from which we have borrowed the term **material tinkering**. The concept of materials experience by Karana et al. (2008) has also been essential to our research, since the objective of our interdisciplinary collaboration has been to study and develop the features of the material in a more holistic way by considering the sensory qualities, meanings of the material, and cultural context alongside the technical characteristics.

The approach for the collaboration has been ***constructive design research***, where constructing something (whether a product, system, scenario, or something else), is central to the research, and it becomes the key means of constructing knowledge (Koskinen et al. 2011). The activities related to prototyping that we discuss here as design "thinging" has been at the center of understanding the behavior of CNC-based structural color in visual design applications. Through laboratory experiments, material tinkering, and prototypes, we have gathered knowledge about the behavior of CNC-based structural color.

Research Design

This exploratory study is based on two interconnected design cases, in which we explored the aesthetic and visual possibilities of the CR effect of CNC-based structural color. The idea was to consider how the edge color of the CR could be used as a visual element in a design context. We have two focal points in the study:

1. Describing the interdisciplinary research and the iterative process of knowledge-building through prototypes, artifacts, material tinkering, and laboratory tests (design “thinging”)
2. The construction of a new colorant through design “thinging”. The role of prototypes, artifacts, material tinkering, and laboratory tests in envisioning a new way to use CNC-based structural color in a meaningful way in the context of design.

We first discuss how the study was run by describing the process through design “thinging” examples. The design “things” are analyzed and sorted into three groups: laboratory tests, material tinkering, and prototypes.

We will then analyze the groups through general prototyping objectives defined by Camburn et al. (2017): refinement, communication, exploration, and active learning. This categorization has laid the groundwork for our data analysis, and therefore, the analysis can be defined as applying a deductive approach (Hirsjärvi et al. 2009).

Objectives of prototyping according to Camburn et al. (2017) are following:

1. Refinement: “The process of improving the design gradually to validate requirements.”
2. Communication: “The process of sharing information about the design, and its potential use within the design team and to users.”
3. Exploration: “The process of seeking out new design concepts.”
4. Active learning: “The process of gaining new knowledge about the design space or relevant phenomena.”

Results

Design Case 1: Pattern Design for a Shoe

In 2017, we attempted to use the CR effect as a visual feature for the first time. During a course at Aalto University, we had a design task to create a shoe prototype containing structural colors from CNCs.

The idea to use the CR effect for the pattern design arose from a mistake. We coated textiles with CNCs in the laboratory (figure 1A), and the experiment yielded an unexpected outcome: the sample resembled a vague camouflage pattern. This result inspired us to experiment with the CR effect (figure 2). Our main idea was to create interesting visual effects by using the rim color to our advantage. The result was a camouflage pattern on a shoe (figure 3), where we engineered the CR to highlight the shape of the colored area. We produced the pattern by combining coated textile pieces with rounded shapes, where the CR behaved in a manner we could predict based on the results shown in figures 1 and 2.

Case 1: Iteration 1

Figure 1 presents laboratory experiments conducted in the initial phase of the project. We explored how CNC-based structural color could be used in a shoe design. At first, we attempted to make the material work on a textile surface, and nylon was one of the primary focus materials based on previous material experiments (Tardy et al. 2019). We had already initially considered the potential of the CR effect as a highlighter of different shapes and as a visual effect. However, the subject required more in-depth study and new experiments.

The laboratory samples in figure 1 show how, due to the CR effect, the CNC-based structural color varies towards the edges of the coated area. We studied the visual appearance of the color around the edges by preparing coatings with different planar shapes. We examined the CR effect by comparing its behavior on sharp and rounded edges and noticed a big contrast.

The materials used in the first iteration were nylon, 3D-printed wood and polylactic acid (PLA).

A minimal amount of material was used for each experiment. The CNCs are expensive, because the material is still in the development stage. In the first experiments, we didn't know if it would be meaningful to prepare larger and more expensive samples, so the experiments were conducted using the scale size typical for laboratory work. The laboratory's equipment was explicitly designed to examine small batches, not to produce large quantities.

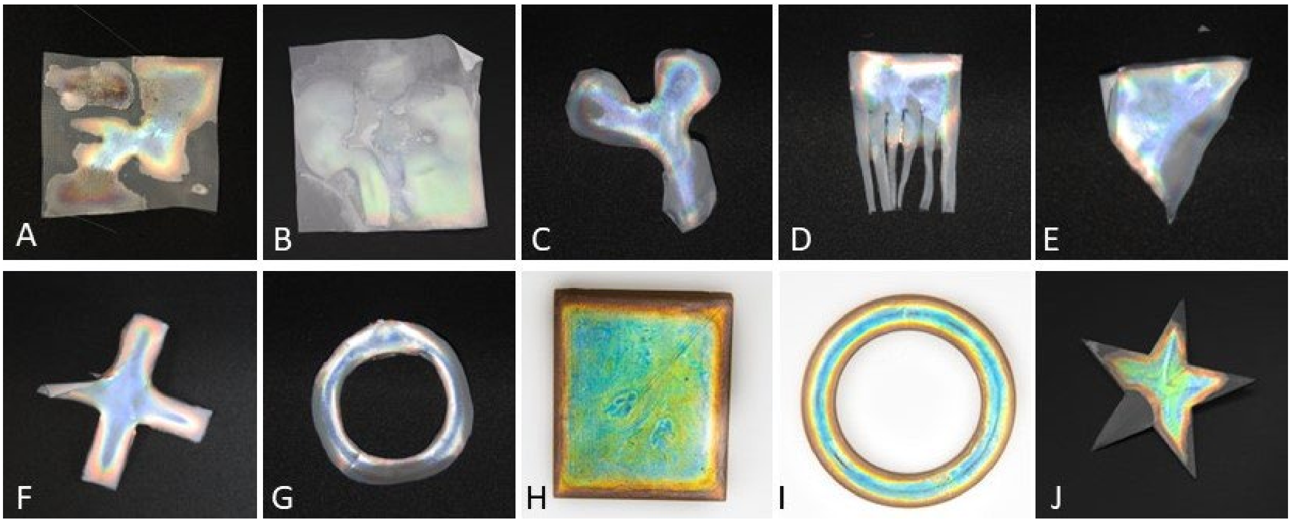


Figure 1. Sample A: Textile coated with CNCs that resembled a camouflage pattern. B: CNC on textile (our attempt to repeat the previous experiment to create a similar camouflage pattern). C–G: CNC on textile. H–I: CNC on 3D-printed wood filament. J: CNC on 3D-printed PLA. Photos H & I: Valeria Azovzkaya

Case 1: Iteration 2

With the second round of experiments, we aimed to combine the more freeform approach of design with laboratory experiments. We further developed the idea of using the CR effect in pattern design and made slightly larger samples (ranging from 5 x 5 cm to 8 x 20 cm). We explored different versions of the camouflage pattern by using a 3D-modeling program to convert patterns into three-dimensional surfaces. We 3D-printed five reliefs that acted as molds for the coating (figure 2: samples A–F). By casting the color on the "peaks and valleys" of the reliefs, we observed how the color behaved on different surfaces.

We simultaneously further explored the camouflage pattern with textile samples. We first drew outlines of the pattern with a pencil and tested these pencil & paper models on the shoe. Based on these models, we cut nylon and cast the CNC suspension on the pieces in the laboratory (figure 2: samples G–H).

We slightly increased the samples' scale so that the appearance of the material would be easier to imagine.

Figure 2. Material tinkering with the camouflage pattern. Samples A–E: CNC on 3D -printed PLA, F: CNC on 3D -printed wood filament, G & H: CNC on textile.

Case 1: Iteration 3

Based on the experiments of the previous rounds, we decided to build a prototype using hand-drawn and hand-cut textile pieces coated with CNC.

We designed the prototype to create a strong material experience with as little CNC as possible. For the first time, we applied nanocrystals onto a "life-sized" object: a shoe. Seeing the material on top of something tangible and real was incredibly motivating to the research group.

The shoe was the first proof-of-concept for us. It showed that it was possible to design a pattern using the CR effect and that we could control the visual effect to an extent. It made envisioning the future of the material more accessible. The design ideas and hunches came into existence in a more concrete way – more people understood our idea and could imagine the possibilities of the colorant.

Figure 3. Shoe prototype.

Design Case 2: "CAMO"

The shoe prototype inspired us to continue designing patterns with the CR effect. We wanted to repeat the method in a different medium. We decided to focus on solid materials in the following experiments, as we had already noticed that soft materials were very challenging base materials for CNC coating due to the fragility of nanocellulose films. While trying different material combinations, we noticed that the colorant worked well on wood. Wood allowed us to develop a "monomaterial", as CNC in itself is wood based. This also opened the possibility of developing an easily recyclable material that does not contain any plastics, and we decided to focus on coloring wood with wood.

In 2020, we explored the CR effect pattern design even further. We participated in the *Designs For A Cooler Planet* exhibition in connection with Helsinki Design Week, and aimed to build three wooden wall elements with CNC and wood. One of these artifacts focused explicitly on the controlled use of the CR effect in pattern design. This time, we did not have an outside brief. We wanted to show our own interpretation of the visual possibilities of the colorant.

In the previous iterations, we noted that round or soft shapes work better than angular or sharp ones to achieve controlled patterns utilizing the CR effect. We also noted that the pattern design should consider the CNC nanocrystals' drying process to fully emphasize the desired shape.

Case 2: Iteration 1

We conducted various experiments to find out which type of wood to use and in which way the processed CNCs would produce the most intense colors (or any color at all). Based on the tests, we ended up with a few types of wood where the CNC suspension worked consistently and produced intense colors.

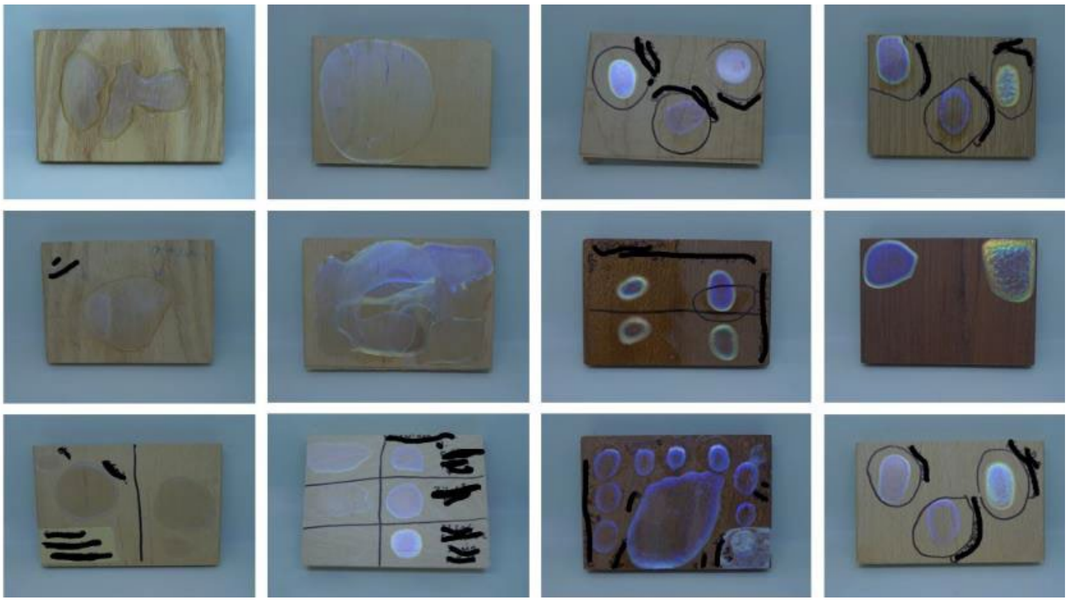


Figure 4. Laboratory experiments with CNC and different wood species.

Case 2: Iteration 2

We designed a new camouflage pattern paying extra attention to the roundness of the shapes so that the CR effect could reproduce the forms easily.

We modeled different 3D versions of the pattern with varying sizes and thicknesses and CNC-milled these patterns. Based on these experiments, we decided the optimal relief height and material combinations. We also calculated the working hours required for coating the wood with CNC to help us estimate how large an artifact we could build within the limits of the schedule.

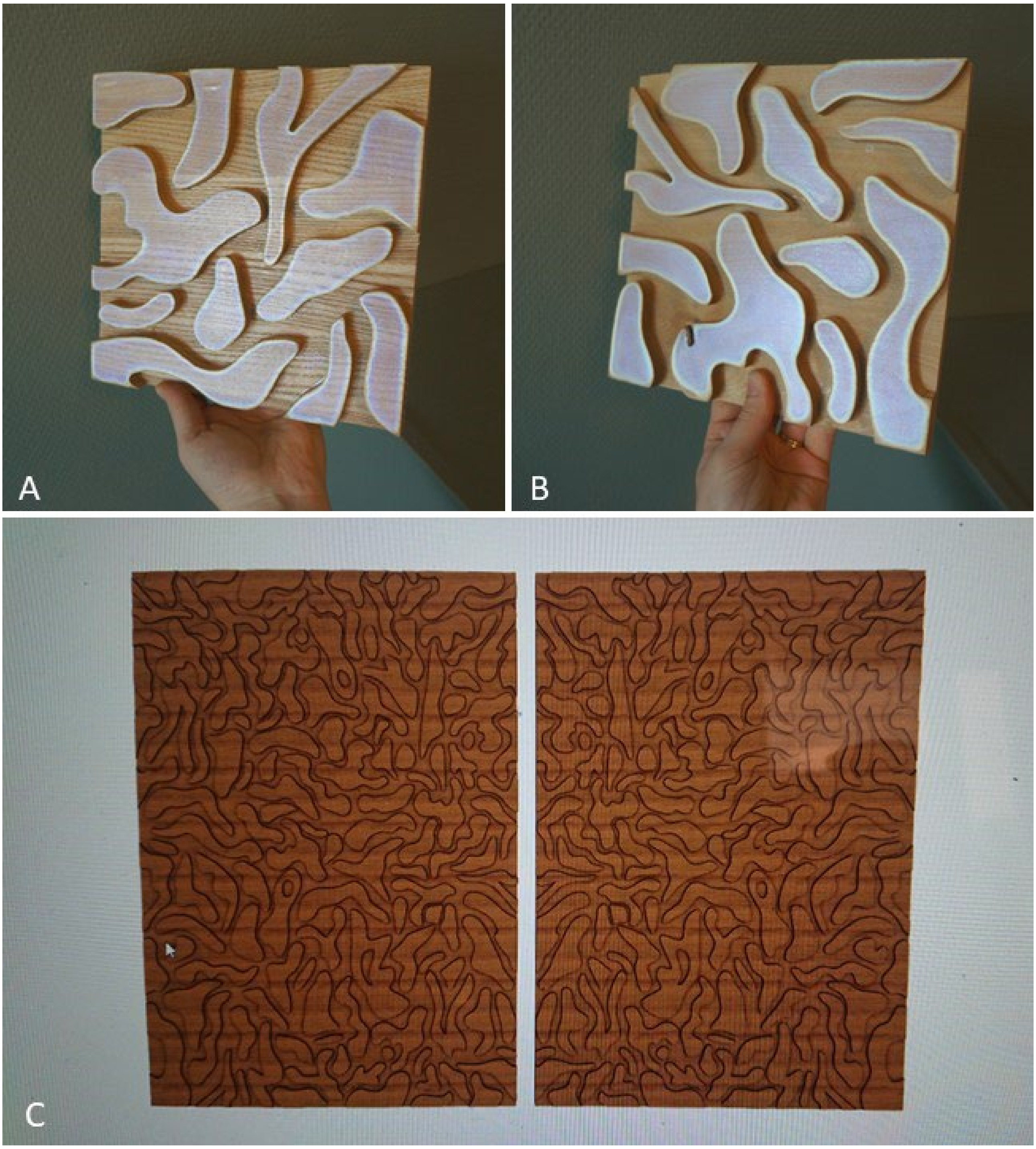


Figure 5. Samples A & B: Tests with different types of wood and relief heights, C: 3D modeling the final plan.

Case 2: Iteration 3

Two 70 x 100 cm wooden sheets were CNC-milled to provide elevated rounded shapes that we coated with the CNCs. Applying the coating on an elevated surface was a technical choice to enhance the quantifiable intensity of the coffee rim effect, but it was also a qualitative aesthetic consideration.

The redshifted edges of the colored area delicately highlighted the embossed wooden pattern and created a gradual change from the natural color of the wood to the iridescence of the CNC-based structural color (figure 6).

Figure 6. "CAMO" in the exhibition. Photos: Esa Naukkarinen

The Characteristic Features for Each Iteration Throughout the Process

Most of the objectives of prototyping defined by Camburn et al. (2017) can be found in all the iteration rounds conducted in design cases 1 and 2. We expanded the prototyping to cover all kinds of design "thinging": laboratory experiments, material tinkering, and prototypes/artifacts.

Laboratory Tests

We started with laboratory experiments that follow the basic principles of materials science. However, the design approach considers possible applications which might not be relevant for basic materials science research. The focus of these tests is to understand a single variant's impact on the colorant. Often, many small tests are conducted at the same time. As in our study, the amount of material used might be minimal (examples in figures 1 & 4). The material may be expensive and difficult to obtain at its development stage, so practical matters need to be considered here.

***Refinement and exploration*:** At this stage of our study, it was not easy to draw a line between the objectives of refinement and exploration. We constructed and fine-tuned our understanding of the material’s behavior and properties during several iterative rounds with different experiments and through conducting various material tests.

These tests focused more on a technical and scientific understanding of the material's properties, for example, why the color could be obtained on some surfaces and not on others. We aimed to solve problems related to the usability of the material and to fine-tune the properties related to the appearance of the color (e.g., tone, intensity, texture, CR effect).

We gathered information, generated a range of new ideas, and then down-selected to a smaller set of concepts to be refined. The main focus was on the technical understanding of the material and improving its features. However, appearance and aesthetics played a crucial role when we down-select what to develop further.

We were exploring and seeking out the possibility of a new design concept through these questions:

1. How could the material be used in a design context?

2. What are the issues that the colorant could solve in the future?

Communication: Discussion played a crucial role in our interdisciplinary collaboration. Professional languages and ways of describing problems and things may vary between fields, and to us, material samples and laboratory experiments were good conversation starters. The physical samples and the performance of laboratory experiments sparked discussion. Questions like "what was it like to experiment?" were discussed within the group, as well as the challenges and successes of the experiments.

We noticed that mood boards and abstract visions might be a bad starting point for communication within the group at the early stages, as too much abstraction resulted in misunderstandings. Instead, the concrete material samples played a key role when discussing and planning the project's next steps. Especially since CNC-based structural color is very challenging to describe with words due to its iridescent and shiny appearance, examining the material samples together by looking and touching was important.

In the second round of laboratory experiments (design case 2), using mood boards and conceptualization in the process worked better as a discussion tool, because we already had experience working together and samples from the previous project to support the ideas that were still relatively abstract.

Constructing physical material experiments helped us identify the differences between concepts and the material's actual behavior. We aimed to plan simple experiments, but in practice, they were often more complex and difficult to conduct than expected. Discussions about failure and unexpected results led to re-evaluating failure as a learning opportunity.

Active learning: Hands-on experience contributes to gaining tacit knowledge about the behavior of the material. Conducting material experiments and discussing the material's properties helped us understand it from different perspectives. The designer's knowledge of the science behind the material's behavior is inevitably thinner than that of the materials scientist. At the same time, scientists may gain new perspectives at their material through this kind of interdisciplinary collaboration.

Material Tinkering

Material tinkering refers to experiments with a freer and more design-oriented approach to studying the material compared to laboratory experiments. In our study, tinkering involves unprejudiced experimentation with the material in environments whose value may not unfold in a straightforward manner in the context of basic materials science research. We used slightly larger samples, because one of the goals of these experiments is also to increase the scale (examples in figures 2 & 5).

Refinement and exploration: With the material tinkering samples, the objectives of refinement and exploration partly overlapped. The material tinkering process gave us a design space where early ideas transformed into a more concrete form. With the tinkering process, we focused more on the visual fine-tuning of the CR effect in the camouflage pattern.

We explored different base materials and designs for the pattern and tried to choose the best alternatives for further development based on these results. The invented and chosen techniques and camouflage patterns were fine-tuned keeping in mind aesthetics, functionality, and the design brief. The choices were also affected by practicalities such as available materials, time limit, facilities, and equipment.

The focus was still very much on learning to manage the material: How can it be used? How can we control the use of the CR effect in pattern design? We also noted design possibilities that were not ideal for the brief (cases under study) but could be valuable in the future.

Communication: The material tinkering samples differed from traditional laboratory experiments, which made them important for interdisciplinary communication. Tinkering samples enabled the material's properties to be discussed more clearly in the context of design. Initial design ideas, hunches, and concepts were communicated more efficiently through material tinkering samples. Concrete examples played a crucial role in communicating ideas – for example, the pattern design was no longer discussed via individual CNC-coated shapes but via small pattern entities.

Active learning: Material tinkering was important for gaining tacit knowledge that goes into using a new material, since the tools for the CNC colorant are yet to be created. The material had to be applied manually in specific conditions. Scaling up to a larger sample size increased the risk of error and material waste. Because of the limited amount of raw material, this needed to be considered carefully. We chose concepts for further development based on our confidence in their success and our capacity to implement the ideas with the skills and tools at hand. After all, our understanding of the material's behavior was based only on a few experiments and some scientific literature, unlike ready-made materials, which sometimes have centuries of tradition behind them.

Prototypes/Artifacts

The experiments aim to bring the material into a presentable form that can also be communicated to a new audience (examples in figures 3 & 6).

Refinement & exploration: With more refined prototypes, we showed the results of our exploration and presented the possibility of completely new design concepts. Ideas were narrowed down to one selected concept to be refined and presented. The information from laboratory experiments and the material tinkering process was used to build something concrete.

Communication: We constructed our findings into a tangible form. Prototypes created a connection between conceptual material and something already existing in the real world. Refined prototypes made the material visible to a new audience because it was in a form that could be exhibited, for example, in design fairs.

The prototype became a communicator of a possible future of the material for both the team and third parties. The prototypes simultaneously provided answers and evoked new questions: What could this material be? How could it be used in the future? Prototypes were tools for envisioning future work: They provoked us and others to think and imagine the use of the material in a new context (e.g., the furniture industry or architecture) and inspired us to think of new ways to apply the idea.

Active Learning: Building something from a new material for the first time is a learning experiment. It was crucial to consider how big a scale we could cover with the colorant. Our solution was to scale up by coating a large area with several smaller colored areas. This way, we could show the possibilities of the material in a new scale size (far larger than in laboratory experiments) and apply the colorant on the wooden surface as risk-free as possible.

Conclusion

This study described how knowledge can be built through constructing design "things" in an interdisciplinary material development project. We analyzed the constructed “things” through objectives for prototypes defined by Camburn et al. (2017). In our project, we noted that constructed "things" can unite people from different fields. Design "things" can act as a medium for collaboration where different perspectives of design and materials science meet and find common answers to questions about the future of materials. Developing environmentally friendly colorants and reducing the usage of plastic- and metal-based materials and toxic ingredients are important goals for the design industry. Nanocellulose-based structural color may offer one option for designers' future color palettes. The formation of structurally colored CNC coatings involves complex processes. The understanding and development of the colorant require considering both its technical and aesthetic aspects. Because of this, the involvement of design in the material development process already at the laboratory phase can help identify all the design possibilities of this new colorant.

Acknowledgements

This work was a part of the Academy of Finland´s Flagship Program under Projects No. 318890 and 318891 (Competence Center for materials Bioeconomy FinnCERES). Konrad Klockars acknowledges support from the European research council under the advanced grant 788489 (BioElCell), the Walter Ahlström foundation, as well as Aalto University. The authors are also grateful Prof. Orlando Rojas for his insightful comments and appreciate the discussions with colleagues in the Fashion/Textile Futures research group at Aalto University School of ARTS and the BiCMAT research group from Aalto University School of CHEM.

References

Burg, S. L., & Parnell, A. J. (2018). Self-assembling structural colour in nature. Journal of Physics: Condensed Matter, 30(41), 413001.

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., ... & Wood, K. (2017). Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science, 3.

Deegan, R. D., Bakajin, O., Dupont, T. F., Huber, G., Nagel, S. R., & Witten, T. A. (1997). Capillary flow as the cause of ring stains from dried liquid drops. Nature, 389(6653), 827-829.

Doucet, S. M., & Meadows, M. G. (2009). Iridescence: a functional perspective. Journal of The Royal Society Interface, 6(suppl_2), S115-S132.

Droguet, B. E., Liang, H. L., Frka-Petesic, B., Parker, R. M., De Volder, M. F., Baumberg, J. J., & Vignolini, S. (2022). Large-scale fabrication of structurally coloured cellulose nanocrystal films and effect pigments. Nature materials, 21(3), 352-358.

Gaver, W. (2012, May). What should we expect from research through design?. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 937-946).

Gencer, A., Schütz, C., & Thielemans, W. (2017). Influence of the particle concentration and marangoni flow on the formation of cellulose nanocrystal films. Langmuir 33:228–234. https://doi.org/10.1021/acs.langmuir.6b03724

Gencer, A., Van Rie, J., Lombardo, S. et al. (2018). Effect of gelation on the colloidal deposition of cellulose nanocrystal films. Biomacromolecules 19:3233–3243. https://doi.org/10.1021/acs. biomac.8b00493

Green, D. S., Jefferson, M., Boots, B., & Stone, L. (2021). All that glitters is litter? Ecological impacts of conventional versus biodegradable glitter in a freshwater habitat. Journal of Hazardous Materials, 402, 124070.

Groth, C., Pevere, M., Kääriäinen, P., & Niinimäki, K. (2020). Conditions for Experiential Knowledge Exchange in Collaborative Research Across the Sciences and Creative Practice. CoDesign International Journal of CoCreation in Design and the Arts, 12: 4, pp. 328-344.

Hirsjärvi, S., Remes, P. & Sajavaara, P. (2009). Tutki ja Kirjoita [Research and Write]. 13–14th edition. Helsinki: Tammi.

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences.

Karana, E., Hekkert, P. P. M., & Kandachar, P. V. (2008). Materials experience: descriptive categories in materials appraisals. In Seventh International Symposium on Tools and Methods of Competitive Engineering-TMCE 2008, Izmir, Turkey (pp. 1-15). Delft University of Technology/Middle East Technical University.

Karana, E., Hekkert, P., & Kandachar, P. (2008). Material considerations in product design: A survey on crucial material aspects used by product designers. Materials & Design, 29(6), 1081-1089.

Kinoshita, S., Yoshioka, S., & Miyazaki, J. (2008). Physics of structural colors. Reports on Progress in Physics, 71(7), 076401.

Klockars, K.W., Yau, N.E., Tardy, B.L., Majoinen, J., Kämäräinen, T., Miettunen, K., ... &

Rojas, O. J. (2019). Asymmetrical coffee rings from cellulose nanocrystals and prospects in art and design. Cellulose, 26(1), 491-506.

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2011). Design research through practice: From the lab, field, and showroom. Elsevier.

Miyagi, K. & Teramoto, Y. (2021). Construction of Functional Materials in Various Material Forms from Cellulosic Cholesteric Liquid Crystals. Nanomaterials, 11(11), 2969.

Mu X. & Gray, D.G. (2014). Formation of chiral nematic films from cellulose nanocrystal suspensions is a two-stage process. Langmuir 30:9256–9260. https://doi.org/10.1021/la501741r

Niinimäki, K., Groth, C., & Kääriäinen, P. (2018). NEW SILK: Studying experimental touchpoints between material science, synthetic biology, design and art. Temes de disseny, (34), 34-43.

Parker, A.R. (1995). Discovery of functional iridescence and its coevolution with eyes in the phylogeny of Ostracoda (Crustacea). Proceedings of the Royal Society of London. Series B: Biological Sciences, 262(1365), 349-355.

Revol, J. F., Bradford, H., Giasson, J., Marchessault, R. H., & Gray, D.G. (1992). Helicoidal self-ordering of cellulose microfibrils in aqueous suspension. International journal of biological macromolecules, 14(3), 170-172.

Schütz, C., Bruckner, J.R., Honorato-Rios, C., Tosheva, Z., Anyfantakis, M., & Lagerwall, J.P. (2020). From equilibrium liquid crystal formation and kinetic arrest to photonic bandgap films using suspensions of cellulose nanocrystals. Crystals, 10(3), 199.

Shang, L., Zhang, W., Xu, K., & Zhao, Y. (2019). Bio-inspired intelligent structural color materials. Materials Horizons, 6(5), 945-958.

Tardy, B.L., Mattos, B.D., Greca, L.G., Kämäräinen, T., Klockars, K.W., & Rojas, O.J. (2019). Tessellation of Chiral‐Nematic Cellulose Nanocrystal Films by Microtemplating. Advanced Functional Materials, 29(25), 1808518.

Yau, N., Klockars, K., Tardy, B.L., & Gaona, O.R. (2020). The Highlight effect in structural color from cellulose nanocrystals. In International Colour Association Conference: Natural Colors-Digital Colors.

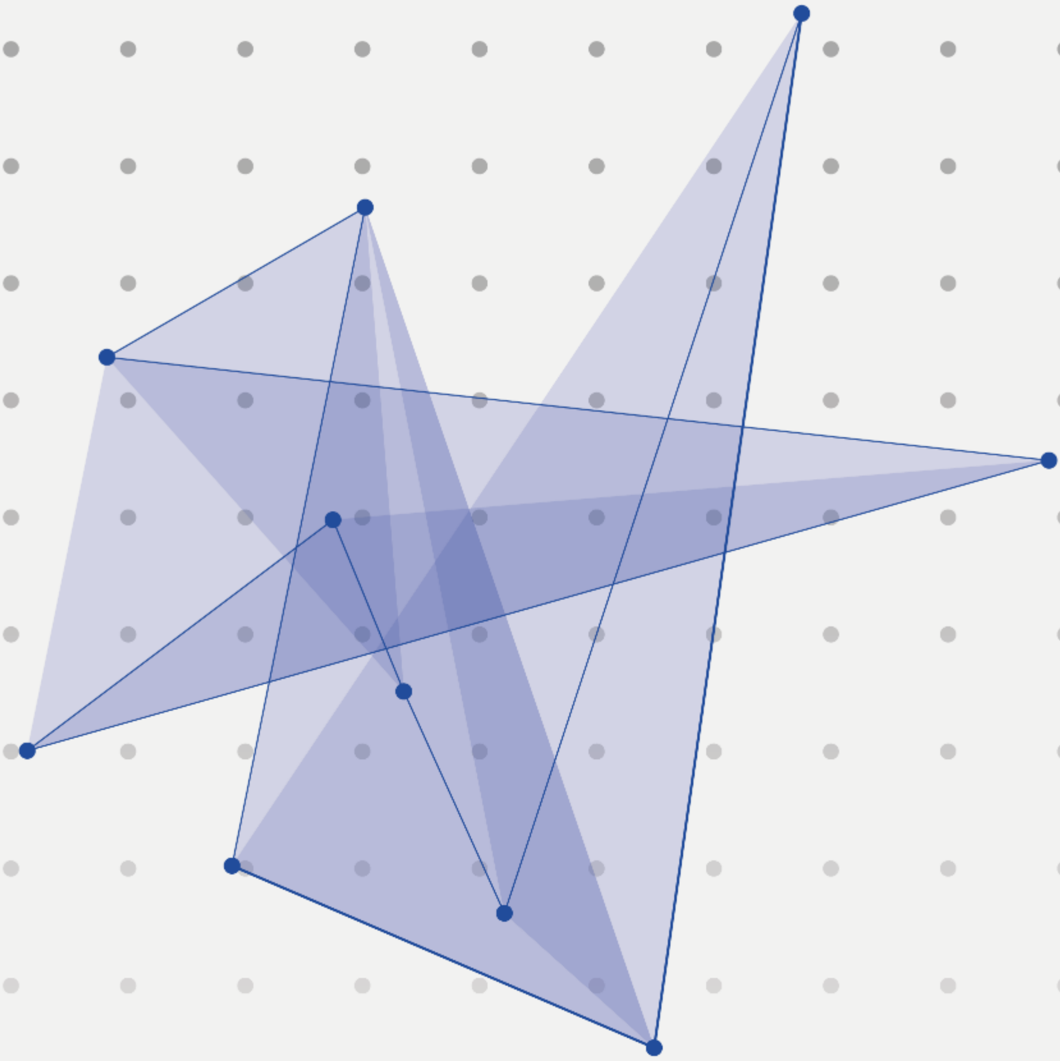
Zhao, G., Huang, Y., Mei, C., Zhai, S., Xuan, Y., Liu, Z., Pan, M., & Rojas, O. J. (2021). Chiral nematic coatings based on cellulose nanocrystals as a multiplexing platform for humidity sensing and dual anticounterfeiting. Small, 17(50), 2103936.

Zhao, Y., Xie, Z., Gu, H., Zhu, C., & Gu, Z. (2012). Bio-inspired variable structural color materials. Chemical Society Reviews, 41(8), 3297-3317

Noora Yau
Noora Yau is currently a Ph.D. candidate under the supervision of Prof. Kirsi Niinimäki in the Department of Design at Aalto University School of Arts, Design and Architecture. Yau obtained her master's degree in Product and Spatial Design at Aalto University. Her research focuses on the prospects of nanocellulose based structural color in art and design applications.

Konrad Klockars
Konrad Klockars is currently a Ph.D. candidate under the supervision of Prof. O. J. Rojas in the Department of Bioproducts and biosystems at Aalto University. Konrad obtained his master's degree in chemical, bio- and materials engineering at Aalto University. His current research focuses on the material properties of structural color coatings obtained through the self-assembly of nanocellulose.

Kirsi Niinimäki
Kirsi Niinimäki is a leading scholar in the field of sustainable fashion. She is an Associate Professor in Aalto university where she leads a research group Fashion/Textile FUTURES. The research done in this group integrate closed loop, bio-economy and circular economy approaches in fashion and textile systems and extends the understanding of strategic sustainable design.



Track 6: Society and Health

- Prototyping assistive devices in india using hybrid manufacturing: a case study on developing ankle foot orthosis (afo) for motor neuron disease (mnd)/amyotrophic lateral sclerosis (als)

- Prototypes as a Structured Information Source in Theory Nexus

- Uncovering Tacit Needs through Prototyping: Designing Post-Harvest Storage Solutions for Marginal Farmers in India

- A virtual reality experiential prototyping tool for the application of anthropometry in complex, confined

Prototyping Assistive Devices in India using hybrid manufacturing: a case study on developing ankle foot orthosis (afo) for motor neuron disease (mnd) / amyotrophic lateral sclerosis (als).

Yash Bohre, IITB-Monash Research Academy
Purba Joshi, IDC School of Design, IIT Bombay
Rowan Page, MADA, Monash University

Abstract

The demand for Assistive devices (AT) is ever so increasing. Still, many potential AT users with varying needs lack access to appropriate AT device that is bespoke for their requirements. This issue is even more significant for people with a degenerative disease, such as people diagnosed with Motor Neuron Disease (MND) or Amyotrophic Lateral Sclerosis (ALS), whose requirements can change even before the device is procured. This is because the design of off-the-shelf AT devices is optimised for mass manufacturing with a one-size-fits-all mentality. Hence conventional manufacturing cannot afford bespoke designs, but hybrid manufacturing has shown the potential to allow bespoke designs in other fields, such as jewellery. Hybrid manufacturing combines different production methods to utilise the pros of individual processes and overcome the con by supporting other methods in unison. In this practice-based design research project, we identified issues faced by people diagnosed with Motor Neuron Disease (MND)/Amyotrophic Lateral Sclerosis (ALS), followed by designing a solution for an identified foot drop problem. We used a hybrid manufacturing approach to prototype our designed product by combining 3D printing and Handcrafting. Testing the developed AT device with our users reinforced our belief in the potential of hybrid manufacturing and how the hybrid manufacturing approach could be an alternative to conventional mass manufacturing methods in providing an appropriate AT device to potential AT users catering to their bespoke requirements.

Hybrid Manufacturing; Digital Fabrication; Bespoke Assistive Devices; MND; ALS

Assistive devices play a crucial role in allowing a physically challenged person to perform their daily tasks independently. According to WHO's World Report on Disability (World Health Organization, 2010), 15% of the world's population (approximately 1 billion) live with some form of disability, of which 2-4% suffer predominantly in functioning. In India alone, 26.8 million people have physical or mental disabilities (GOI, 2021). Though ATs have the potential to have a significant benefit (in case of physical disability) for their users' specific issues in the Product life cycle of an AT device prevent them from large-scale adaptation. Moreover, there is a high abandonment rate among those who eventually procured them, as 1 in every 3 AT devices ends up being abandoned (Phillips & Zhao, 1993). The study (Phillips & Zhao, 1993) also identified critical predictors for the high abandonment rate of AT;

these include

1. **Lack of user involvement in device selection:** In most cases, a physician will choose a device for their patients with almost no input from the users (Phillips & Zhao, 1993).
2. **Difficulty in device procurement:** It takes a significantly long time for a person to receive an AT device from when it is initially recommended by a doctor (Hurst & Tobias, 2011).
3. **Poor Device Performance:** In many cases, the device does not perform as per the user's expectation or requirement to do a particular task well (Phillips & Zhao, 1993).
4. **Change in user's need/ability:** By the time the AT device reaches the person/user, they may no longer require it due to improvement or decline in their conditions (Phillips & Zhao, 1993).

In their study (Phillips & Zhao, 1993), Phillips and Zhao suggested that the large-scale abandonment of ATs can be reduced by developing policies and services involving user engagement and considering the long-term usage of ATs. To improve the overall access to Assistive Devices, alternate design and manufacturing methods must be explored, such as the participatory design approach, skilled handcraft, Do It Yourself (DIY), digital fabrications etc. Many AT users make modifications to their AT devices based on their current individual requirements and changing medical needs rather than relying on general-purpose devices built by large-scale manufacturers that are usually a poor fit for most users (Hurst & Tobias, 2011). This is because, in an off-the-shelf medical device, *It is Difficult to come up with a design that fully satisfies all functional and manufacturing requirements. Usually, some requirements will need to be compromised. Engineers do this in a systematic manner and call it optimisation* (Ravi, 2018).

On the other hand, relying entirely on a DIY solution like digital fabrication alone cannot meet the complex needs of devices like prosthetics. These include limitations such as DIY materials might not be appropriate for long-term usage as they may damage the skin (Hofmann et al., 2016), so other bio-compatible materials need to be explored to ensure the users' safety and proper functioning of the AT device (McDonald et al., 2016). Limited access to Prototyping tools (Computer and 3D printer) and learning tools (for CAD) prevent some AT users from benefiting from DIY (Hofmann et al., 2019). Lack of experience in DIY activities leads to reduced confidence in personal skills making people hesitant to make their own AT devices or for the people they care for (Hook et al., 2014).

This leads to the unavailability of appropriate AT devices for those who need them. One such user group is the people diagnosed with MND/ALS. Motor Neuron Disease (MND) is a neurodegenerative disease in which motor neurons gradually stop signalling the muscles on how to move. Amyotrophic Lateral Sclerosis (ALS) is the most common form of MND. It is caused due to neurodegeneration (decay of neurons) in the brain and spinal cord, affecting the Peripheral Nervous System as well. Characterised by weakness and wasting in the person's upper and lower limbs, ALS is a life-shortening disease affecting how the person walks, talks, eats, drinks, and breathes, with the symptoms worsening over time. Since there is no cure for ALS yet, the daily tasks of people with ALS are supported by Assistive (AT) devices. These devices range from simple non-automated devices like grippers, orthosis and walking sticks to complex automated devices like powered wheelchairs and robotic prostheses. In MND/ALS, the role of AT devices changes at different stages of the disease (Sane & Sharma, 2016). In the initial stage of the disease, an AT device is used to prevent the functional decline or atrophy of muscle, while in the later stages, the role of AT devices is to restore the functional independence of a person (Sane & Sharma, 2016). The requirements of MND/ALS users vary more quickly as the disease progresses, and conventional AT devices can not suffice for the people's individual varying needs. Conventional ATs are mass-produced on an assembly line, optimising each step to increase production capacity and reduce production costs. A similar production methodology cannot be applied when making bespoke medical devices, the design of which differs based on the different needs of individual users. Mass Production methods are optimised for similarities in design & parts and, lack the capacity to make individual modifications, and can hardly support Bespoke designs. So, alternative manufacturing methods need to be explored that afford to manufacture varied designs and parts as well as allow modification catering to the specific needs of individual users. A hybrid approach to manufacturing AT devices can have a significant benefit in supporting bespoke designs and modularity. Hybrid manufacturing combines different production methods utilising the pros of individual processes and overcomes the con by supporting other methods in unison. For example, Rapid prototyping techniques like 3D printing are now extensively being used in the jewellery industry in unison with traditional mold making and casting to make jewellery. With digital workflow, a designer could make the intricate details faster, which used to be a time-intensive manual labour earlier. This eventually leads to a faster turnaround time and reduced costs (Mahal & Karan, 2009).

With ever so growing requirements for Medical and Assistive devices in India (Kang & Ma, 2017), the demand is not being satisfied by the supply of conventional mass-market devices either due to the unavailability of appropriate devices in the Indian market or due to the exorbitant price they come with (Mahal & Karan, 2009). This has led to the emergence of an unorganised sector of hand-crafted medical devices in India. But, the statistical data about the market share of the same is unavailable (Mahal & Karan, 2009). The AT devices from the unorganised sectors satisfy only the essential requirement and can provide an affordable device to the end AT user. However, it compromises the safety requirements, as no governing body regulates it. Such local manufacturer possesses skills to prototype bespoke devices and make tweaks based on the user's individual needs. However, they lack the ability to make an appropriate design of the terminal components of a device. For example, a socket used in a prosthesis requires 3D scanning or mold preparation of the amputee limb to be an accurate fit and prevent future injuries. So the objective of this project was to augment the skills of local manufacturers with Rapid Prototyping techniques like 3D printing and prototype an appropriate AT device for ALS users. The project was a design-centric exploration. The following section of this paper discusses the case study of the complete design and manufacturing process of developing an Assistive Device for people with ALS and using hybrid manufacturing.

Methodology

Developing Assistive devices can largely benefit from the Participatory Design Approach. Keeping the stakeholders in the design and testing loop can lead to co-creating meaningful solutions for the end-users. So, for this project, we decided to use Stanford's 5 step design thinking process as a guide for participatory design, with the last three steps as the iteration loop. These steps include.

1. **Empathize:** Understand the users so that they can articulate their needs better.
2. **Define:** Define the latent needs of the users.
3. **Ideate:** Generate concepts to cater for the defined needs.
4. **Prototype:** Develop a prototype of the finalised concept.
5. **Test:** Take the prototype to the users to test and see if it can fulfils their needs.

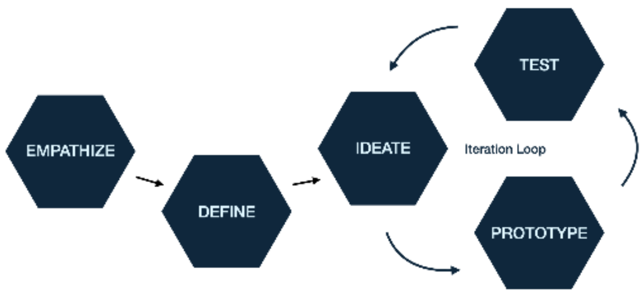


Figure 1: 5 steps of Stanford Design Thinking Method, with Iteration loop.

The following subsections thoroughly present how these five steps have been utilised in this project.

Empathize: Primary Research

The primary research for the project included multiple rounds of interviews at NeuroGen Brain and Spine Institute, Navi Mumbai, India, with five users between the ages of 32-62 diagnosed with MND/ALS. The first interview was conducted with all the users independently in the form of a structured interview during their OPD assessment under medical supervision. This was followed by an unstructured in-person interview with individual users and their family members to better understand the symptoms and difficulties faced by them daily. The interview findings were then discussed with clinicians, and their symptoms were mapped on major categories inspired by ALSFRS Score (Cedarbaum & Stambler, 1997). Table 1 shows the mapping of symptoms experienced by individual users (alphanumerically coded).

Table 1: Different Symptoms shown by the Users

Users	U1	U2	U3	U4	U5
Age	43	52	62	31	42
Stage (Early: E / Mid: M)	M	M	E	E	E
AT usage (High: H / Low: L)	H	L	L	L	L
Symptoms Shown					
Bulbar Symptoms (Speech)	✓	✓			
Bulbar Symptoms (Swallowing)	✓	✓			
Respiratory Insufficiency					

Loss of Fine Motor skills (Grip)	✓				✓
Shoulder Drop (Bilateral/Unilateral)	✓				
Muscular Fasciculation		✓	✓	✓	✓
Muscle Atrophy (Upper Limb)	✓	✓			
Issues with Dressing and hygiene	✓			✓	
Mobility Issue	✓	✓	✓	✓	✓
Muscle Atrophy (Lower Limb)	✓	✓		✓	✓
Foot Drop	✓		✓	✓	✓

Of the five users interviewed, all the users faced moderate to major difficulty in mobility, either due to the loss of muscle, foot drop, or both. As issues with mobility lead to a greater dependency of the user on their family, hence every user puts a greater emphasis on muscle loss in the lower limbs and a desire to reverse the same. Since MND/ALS is a non-reversal neurodegenerative disease, clinicians couldn't promise false hope to the users to regenerate lost muscles but did acknowledge the possibility of improving mobility via Assistive Device. Hence for this project, we decided to work on improving the user's mobility by designing AT device.

Define: Need Analysis

On further discussing the issue of mobility with clinicians, foot drop was also studied. In ALS/MND, due to weakness of the muscles responsible for lifting the front part of the foot, the users are unable to raise the forefoot and face a condition known as foot drop. This leads to irregular gait and frequent falls of the users. An ankle-foot orthosis (AFO) assistive device is used to correct this. It controls the position and motion of the ankle by arresting the ankle muscles and forefoot in a fixed/rigid place. But the Conventional AFOs (figure 2A) have various issues. These include but are not limited to AFOs being **very bulky,** making it difficult for the user to walk while wearing these heavy-weight AFOs. Other Foot Orthoses use metal bars (figure 2B) to control foot drop. This also makes the shoe bulky and challenging for the user. It is also rigid, leading to stiffness and pain in the muscle. U1 had tried multiple types of AFOs and stated, "they are very heavy, it is very difficult for me to lift the foot for walking, I can't lift my foot with these heavy AFOs, I want something that is lightweight". The AFOs currently present in the market (figure 2A and 2B) are **aesthetically unappealing** and draw unwanted sympathetic attention for the user. U3 states, "I can't wear these (figure 2B) to work. Everyone will look at me and ask what happened? Are you all right."

Figure 2: Ankle Foot Orthosis (AFO) available in Indian and International Markets

We also studied the work conducted by Gaurav Nandan and Dr Purba Joshi titled ‘Redesigning Footwear for MND Patients’ (Nandan & Joshi, 2020).They studied the foot drop issues faced by people with ALS and developed footwear (Figure 3) to tackle the specific issue of foot drop. The footwear design included a bent Arch that supported the foot from the bottom and wrapped around the Achilles tendon. The preliminary testing with people with ALS revealed that this design prevented the foot from dropping and provided an ample rebound while walking. But there were a few issues with the design that were required to be addressed to make the footwear more acceptable and accessible to the users. This included redesigning straps to make it easier for users to wear and remove the footwear with the least effort and ensuring a comfortable fit in multiple stages of foot swelling (in ALS, foot swelling varies a lot throughout the day). Another primary concern was the manufacturability of the shoe; the arch was built separately using DIY techniques (cutting, grinding and heat gun) and then assembled in the footwear by upcycling an existing shoe.

Figure 3: Foot Lift Shoe Designed by Gaurav under the Supervision of Purba Joshi as a Student Design Project at IIT Bombay

This process is not scalable. Hence, design for manufacturing was a key to the redesign process. Hence based on the user and product research following Functional Requirements were defined:

1. **Functional Prototype:** That provides the full range of features and allows realistic feedback on its form, fit, feel and function (Ravi, 2018).
2. **Flexible in Nature:** To aid foot movement to some extent and not rigid to prevent muscle soreness.

3. **AT in Disguise:** A footwear that is Aesthetically Appealing and does not look like an AT device to avoid unwanted sympathetic attention.
4. **Design for Manufacturing:** A design that can be reproduced anywhere with production instructions.
5. **Easy to use and maintain:** Users should be able to use and maintain it like a regular shoe and not like an AT device.

With the functional requirements set in place, we started ideating the Foot lift shoe.

Ideate: Design

Informed by the learnings from the previous shoe project, we kept the principle of a bent arch to support the forefoot and provide ample rebound while walking. We redid the entire design of the straps as well as the arch itself. The initial concept sketches were shown to two users (U1 and U3) to study their perceptions about the initial designs and get their feedback/input. The designs were also presented to clinicians for biomechanical feedback. Figure 4A shows the initial conceptual design.

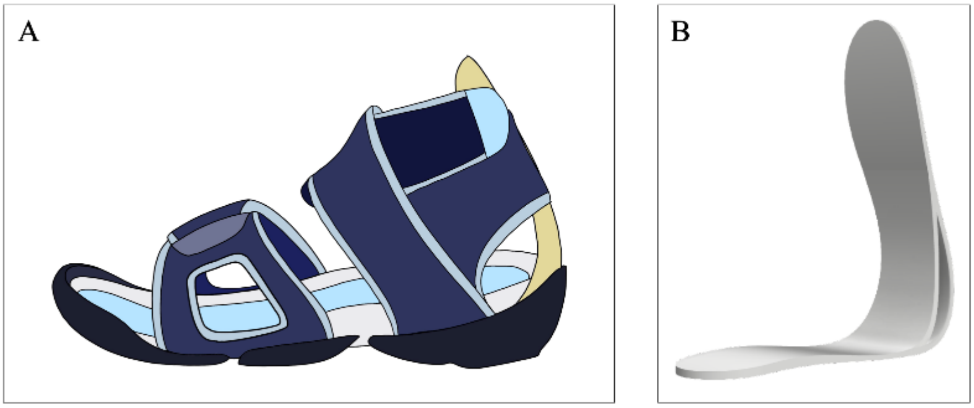


Figure 4: (A) Redesigned Concept of Shoe to contain foot drop (B)CAD Models of Heel Arch to be 3D Printed

This was followed by dividing the shoe into individual components for detailed design. The heel arch was modelled in Autodesk Fusion 360 and 3D printed (FDM) to explore the form. Figure 4B shows the iteration of the Arches. After finalising the design of the Arch, we moved to the prototyping stage.

Prototype: Hybrid Manufacturing

We started exploring hybrid manufacturing techniques to prototype the shoe, where the footwear could be made partly by Rapid Prototyping (Digitally fabricating the arch) and partly with the help of skilled workers (shoemakers).

For the first prototyping stage, Multiple materials and the associated manufacturing process were explored to manufacture the arch. Polyamide PA12 was best suited for the design requirements, and the arch could be made using Multi Jet Fusion (MJF) or Selective Laser Sintering (SLS). Due to these processes being very expensive, Polyamide PA12 was rejected. Another option was using PLA Sheet (Cutting and Heat molding). It required a lot of person hours or manufacturing a separate die for the same, so for prototyping to be accessible, it was also rejected. Using elastomers was another option considered that required vacuum casting for manufacturing. Vacuum casting was an alternative that could be used if the volume was more significant, but for the prototyping, it was out of scope and inaccessible. Finally, We chose flexible Polylactic Acid (PLA) as it could be molded easily using a Fused Deposition Modeling (FDM) machine, the most commonly available 3D printing technology. Multiple scaled iteration of the redesigned Arch was prototyped in flexible PLA using FDM. The print direction was kept perpendicular to the plane where the Arch moves/bends during footwear usage (figure 5A). This ensured a sturdy and durable build. In the next iteration of the Arch, the side was flattened to have the design built in FDM without any support materials. An inward bend was added to provide a pre-tension (figure 5B) when the arch is bent to fit in the foot's natural position during usage. 3D printing allowed a quick turnaround time for making prototypes with iterative modifications, keeping the features that satisfied the functional requirements and modifying those that didn't. Figure 5C shows a 1:1 scale prototype of the final Arch to be fitted in the shoe.

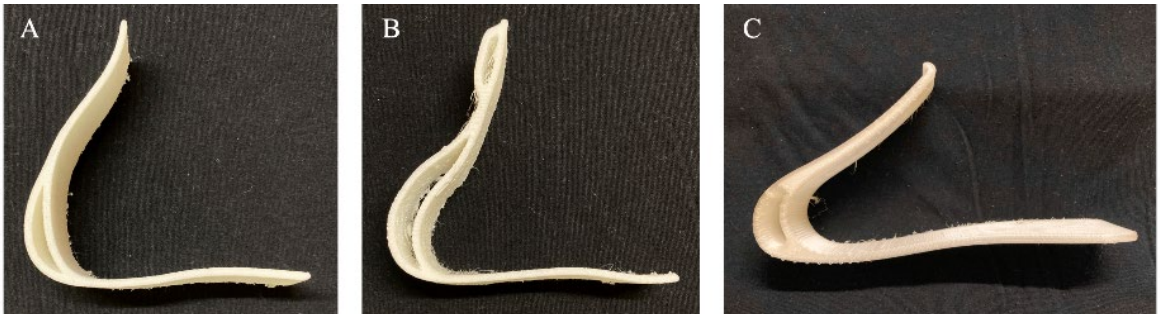


Figure 5: (A)3D printed Heel Arch (B)Heel Arch iteration with strap mounts and pre-tension (C) 1:1 Scale prototype of the Final heel Arch 3D printed in flexible PLA to be fitted in the Shoe

For the second step of the prototyping, a local shoemaker was identified in Dharavi, Mumbai, to help build the functional footwear prototype as per the final design.

Figure 6: Workshop Setup of the Local Shoemaker

The shoemaker provided multiple options for the outsole based on the functional requirements of flexibility and aesthetics. An outsole was required that had enough room to host the arch, along with an insole, without compromising the structure. India has varied terrain and weather conditions. Hence a durable outsole was required. Based on these requirements, an all-purpose sports shoe outsole was finalised. The 3D-printed Heel arch couldn't be kept in contact with the skin for longer duration; hence a soft-touch cover and cushioning for the same for needed. In this situation, the shoemaker's experience came in handy in choosing an apt fabric material to cover the 3D-printed arch (Figure 7A) so that the shoe can be worn longer without affecting the skin it is in contact with and be stuck firmly on Heel Arch and the outsole. Another requirement was to select materials for straps that are non-stretchable so they can arrest the ankle yet be breathable for comfort. Figure 7B shows the Fabric straps being glued and stitched to the outsole. Once the entire shoe was assembled, the complete assembly instruction for the arch, outsole, insole and straps were articulated to be followed for a future iteration of the shoe. Figure 7C shows the final functional prototype of the shoe that was taken to the users for testing and developing future iterations based on the user review of the footwear design.

Figure 7: Multiple Stages of Assembly (A) 3D Printed Heel Arch covered in Fabric, (B) Straps Stitched and glued to the outsole, (C) Final functional prototype.

Prototyping the shoe partly by 3D printing and partly by handcrafting saved significant research and development time. 3D printing allowed rapid prototyping of arches with a faster turnaround time and having an expert shoemaker reduced the material procurement and assembly time of making a finished product. We made the prototype based on the U1's foot size.

Testing: User Testing and Iterations

Once the functional prototype of the shoe was ready, we tested it with the user (U1) under medical supervision (figure 8A). The testing showed that the user could not lift the forefoot as much as we expected. On discussing with the clinicians why the product was failing, we realised that the length of the 3D printed arch was not appropriate, the positioning of the straps was not apt to hold the forefoot firmly, and the outsole was more flexible. Clinicians advised us to use a more rigid outsole and increase the arch length to support the forefoot. We also used an external strap to determine the accurate position where the straps should be and tested the prototype (figure 8B). The prototype worked to an extent, as it could lift the forefoot with modified straps. We noted the three significant changes to be made in the next iteration.

1. Length of the Arch to support the forefoot
2. Positioning of the Straps
3. Stiffness of the sole.

Figure 8: (A) Testing the first prototype with U1, (B) Testing with the modified position of straps.

With only a few commands, we could digitally modify the design of the arch in Autodesk Fusion 360 and increase the length of the Arch. Since we already had the 3D printing parameter of flexible PLA from our previous prototype. Hence, we could prototype the new arch with a faster turnaround time. Since our previous shoemaker was unavailable this time, we identified a different shoemaker and briefed him on the modified design and the production instructions developed during the first prototype. With a short briefing of 30 minutes, the new shoemaker understood the entire process and was able to deliver the new shoe in under 5 hours (including the briefing time).

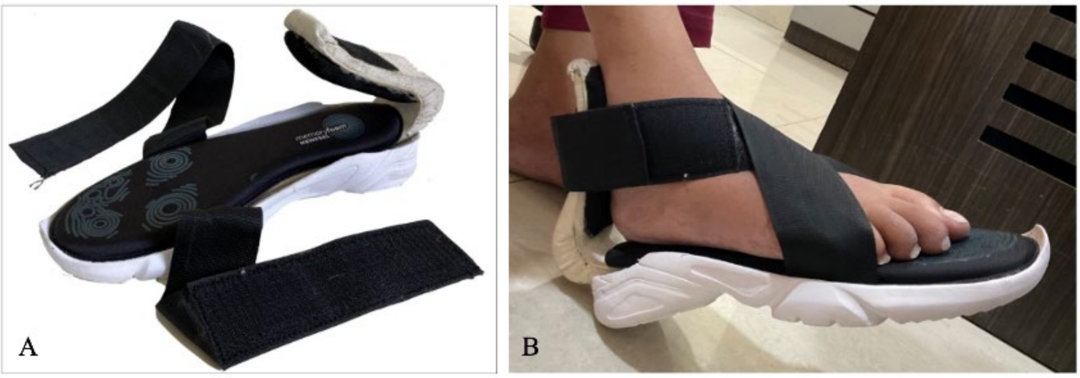


Figure 9: (A) Second Prototype (B)Testing of the Second Prototype.

We tested the second prototype with User 1 (figure 9B), and the shoe successfully contained the footdrop and provided ample lift to the forefoot. We also made the second prototype shoe in size bigger to test it with another user (U3). Moreover, since the mechanism is dependent on the arch and forefoot straps, testing a bigger shoe also showed positive results with the user (U1) with a smaller foot size. There were a few suggestions for improving the shoe's comfort, but overall, the shoe could satisfy all the functional requirements we defined in section 2.2.

This is an ongoing project, and as of writing this paper, we are developing a 3rd iteration of the shoe for long-term testing and review.

Results and Discussion

Hybrid Manufacturing has proven advantageous in the development process of the AFO shoe, as it has overcome the limitations of prototyping through traditional mass manufacturing and bespoke digital fabrication. The bespoke designs and parts made possible by hybrid manufacturing allowed for quick modifications that catered to the specific needs of individual users. The requirements of the AFO shoes for ALS were defined by the functional requirements of ‘arresting footdrop’, ‘lifting forefoot’, ‘having aesthetically dignified AT’, and ‘being wearable for long hours’, along with the manufacturing requirements of ‘a functional prototype’, ‘strength for sustained use’, and ‘bespoke sizes’. We used hybrid manufacturing techniques to Prototype our design, partly by Rapid Prototyping, 3D printing the heel arch, and partly by handcraft, with the assistance of skilled shoemakers.

Using 3D printing (FDM) to prototype the heel arch for the shoe allowed for individual testing and modifications with a faster turnaround time. Once the design was finalised, the 3D-printed arch was given to a professional shoemaker to assemble the shoe. The shoemaker's real-world experience making bespoke shoes provided valuable knowledge about materials suitable for different terrains and climates, saving research time and speeding up material selection and shoe production. They also helped source the chosen materials as they’re stakeholders in the local shoe industry's supply chain. After prototyping the first shoe, we developed production instructions to recreate another shoe quickly. The first shoe took around 16 person-hours to make (excluding 3D printing time), but the time to make the second shoe was reduced significantly to just 5 hours, including a 30-minute briefing on the production instructions, for a new shoemaker with no prior knowledge of this design. This illustrates how standardising production instructions can also significantly reduce production time in hybrid manufacturing.

Using traditional mass manufacturing or digital fabrication methods as a standalone method to prototype bespoke medical devices has to make compromises with functional or manufacturing requirements. On one end, prototyping a bespoke medical device using traditional mass manufacturing methods can lead to higher costs due to the associated part-specific tooling, while making the same design using digital fabrication can lead to unfulfilled functional requirements. Combining the unique benefits of these processes and overcoming the limitations is a crucial benefit of Hybrid Manufacturing. In the context of India, Hybrid Manufacturing presents an excellent opportunity for the field of Medical Device Design, given the country's large population of skilled workers and emerging status as a manufacturing hub. Our case study demonstrates the potential of Hybrid Manufacturing techniques to prototype assistive devices that are more meaningful and user-friendly for end-users. In the case of medical and assistive devices, a functional prototype is essential, and hybrid manufacturing provides an excellent alternative to conventional methods for designers to develop functional prototypes.

Conclusion

The demand for AT devices is growing worldwide, and there is a need to explore alternate methods to manufacture them. Our project aims to demonstrate the potential of hybrid manufacturing in providing appropriate assistive devices with bespoke designs that cater to users' unique requirements. This is an ongoing project, and we will test the prototypes with multiple users to develop future iterations. Clinical trials will follow, and we will work towards developing a go-to-market product. Through this practice-based design research, we will gain valuable knowledge to inform a design framework for developing AT devices that meet the AT requirement of people with individualised and varying needs. This will enable designers to prototype bespoke AT devices more efficiently and tailor them to meet specific requirements. By leveraging hybrid manufacturing, there is a potential to enhance the timely prototyping and delivery of appropriate AT devices for people with ALS, thereby improving their quality of life and independence.

Acknowledgements

This project was conducted as part of a joint PhD research between the Indian Institute of Technology Bombay, India, and Monash University, Australia (Project Number ID00985. The user research and testing were conducted ethically with approval from the Institutional Review Board (IRB) at the Indian Institute of Technology Bombay under Proposal No. IITB-IRB/2022/023. NeuroGen Brain and Spine Institute, located in Navi Mumbai, India, provided clinical support for this project.

References

Cedarbaum, J. M., & Stambler, N. (1997). Performance of the Amyotrophic Lateral Sclerosis Functional Rating Scale (ALSFRS) in multicenter clinical trials. Journal of the Neurological Sciences, 152, s1–s9. https://doi.org/10.1016/S0022-510X(97)00237-2

Hofmann, M., Burke, J., Pearlman, J., Fiedler, G., Hess, A., Schull, J., Hudson, S. E., & Mankoff, J. (2016). Clinical and Maker Perspectives on the Design of Assistive Technology with Rapid Prototyping Technologies. Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility, 251–256. https://doi.org/10.1145/2982142.2982181

Hofmann, M., Williams, K., Kaplan, T., Valencia, S., Hann, G., Hudson, S. E., Mankoff, J., & Carrington, P. (2019). "Occupational Therapy is Making": Clinical Rapid Prototyping and Digital Fabrication. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3290605.3300544

Hook, J., Verbaan, S., Durrant, A., Olivier, P., & Wright, P. (2014). A study of the challenges related to DIY assistive technology in the context of children with disabilities. Proceedings of the 2014 Conference on Designing Interactive Systems, 597–606. https://doi.org/10.1145/2598510.2598530

Hurst, A., & Tobias, J. (2011). Empowering individuals with do-it-yourself assistive technology. The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility - ASSETS '11, 11. https://doi.org/10.1145/2049536.2049541

Kang, J., & Ma, Q. (2017). The role and impact of 3D printing technologies in casting. China Foundry, 14(3), 157–168. https://doi.org/10.1007/s41230-017-6109-z

Mahal, A., & Karan, A. K. (2009). Diffusion of medical technology: Medical devices in India. Expert Review of Medical Devices, 6(2), 197–205. https://doi.org/10.1586/17434440.6.2.197

McDonald, S., Comrie, N., Buehler, E., Carter, N., Dubin, B., Gordes, K., McCombe-Waller, S., & Hurst, A. (2016). Uncovering Challenges and Opportunities for 3D Printing Assistive Technology with Physical Therapists. Proceedings of the 18th International ACM SIGACCESS Conference on Computers and Accessibility, 131–139. https://doi.org/10.1145/2982142.2982162

Phillips, B., & Zhao, H. (1993). Predictors of Assistive Technology Abandonment. Assistive Technology, 5(1), 36–45. https://doi.org/10.1080/10400435.1993.10132205

World Health Organization. (2010). Medical devices: Managing the mismatch: an outcome of the priority medical devices project. Dispositivos Médicos: La Gestión de La Discordancia: Un Resultado Del Proyecto Sobre Dispositivos Médicos Prioritarios. https://apps.who.int/iris/handle/10665/44407

Sane D. H., Sharma D. A. (2016). ALS/MND Guide Book For Patients & Families. (p. 234-248). Neurogen Brain and Spine Institute and Asha Ek Hope Foundation

Nandan G., Joshi P. (2020). Redesigning Footwear for MND Patients. Design Research Seminar 2020, IDC School of Design, IIT Bombay.

Ravi, B. (2018). Develop - Make Novel Devices in The Essence of Medical Device Innovation (p. 69).

GOI. (2021). Persons with Disabilities (Divyangjan) in India - A Statistical Profile : 2021. Government of India, Ministry of Statistics and Programme Implementation.

Yash Bohre

Yash Bohre is an early-stage PhD Scholar jointly supervised at IIT Bombay and Monash University. He holds a Major in Mechanical Engineering and a Graduate degree in Industrial Design(M.Des.). He has experience in user research and projects focusing on 'Design for Healthcare'. His current PhD research primarily involves identifying the gaps between the needs of ALS patients and the available Assistive devices and developing design interventions to fulfil those needs.

Purba Joshi

Purba Joshi is an Associate Professor of Industrial Design at IDC School of Design, IIT Bombay, India. She holds a Major in Electronics and Telecommunication Engineering and a graduate degree in Industrial Design(M.Des.). She completed her PhD in CAD and creativity from IDC School of Design, IIT Bombay. She works extensively in the area of product design for healthcare. Other research and consultancy work areas include packaging design and designing for special needs.

Rowan Page

Rowan Page is the Program Director of Industrial Design at Monash University, Melbourne, Australia. Rowan conducts research within the Design Health Collab – an interdisciplinary research group at the intersection of design and health. His

research is driven by exploring the roles of design practice in supporting translational research and medical device development. Completing an industry-embedded PhD in collaboration with Cochlear in 2018, Rowan continues a collaborative practice-based approach to research through partnerships with Blundstone, Cabrini Technologies and researchers in IT, Engineering, Medicine, Nursing and Health Sciences. He is an award-winning Industrial Designer and has worked at several leading Australian design consultancies and at General Motors Holden. His research practice has led to diverse traditional and non-traditional research outputs, including multiple manufactured objects, exhibitions, patents and journal articles.

Prototypes as a Structured Information Source in Theory Nexus

Renata Dezso, Moholy-Nagy University of Art and Design Budapest

Abstract

In this paper, I analyse the role of prosthetic prototypes developed during my doctoral research (completed in 2022), generating critical thoughts and new insights into our value system as it relates to human-centred societal challenges. The investigation settled in the experimental approach of Research through Design alongside a qualitative case study combined with the power of critical disability studies to advance space for understanding relationships between phenomena and theory. To focus on the central questions from a particular single case study project, I worked with Luca Szabados (a highly creative independent artist with a congenital disability) to craft a prosthesis using digital technology. The role of prototypes in the research not only encompasses the experimental and physical nature of the study but also creates links in the chain of knowledge development and carries evidence data. The prosthetic prototypes guided reflections on human-centred societal challenges as a non-verbal modelling media. The tangible material nature of the prototypes provides the possibility of operating with a set of 'boundary objects' within discussions that include the enactment of latent perspectives. The prosthetic prototypes encode a tangible chain of thoughts as a result of the design synthesis of knowledge and research questions with the central links of the method. The data of the artefacts construct the evidentiary values of the research and enable an exploration of philosophical and strategic approaches to co-Ability. The term 'co-Ability' is rooted in the critical approach of posthuman disability studies. It serves as a broad umbrella term under which we can reconsider the potentials of various entities (biological and artificial) that enhance the shared competencies of those entities rather than dwell on the oppressive nature of human-centred norms. In this research, the discursive prosthetic prototypes thus carry a profound and integrative argument that significantly connects with the general viewer and represents the theory development.

Research through Design; co-Ability; discursive prototypes; prosthesis; disability studies

The aim of this paper is to outline the role of prosthetic prototypes developed during my doctoral research (completed in 2022) in generating new critical and new insights into our value system concerning human-centred societal challenges. This research began with a focus on the caring attitude to prosthesis development inspired by the work of Peter H. Jones. He endorses positivist certainties in contemporary digital technologies for inclusive and transitive approaches (Jones, 2013). From here, the initial task and concept were repositioned (conceptual repositioning in design) from a place of problem-solving to one of bringing the situational nature of the design prototype into focus (Buchanan, 1992). I settled on the framework of a single design case study project that aimed to use digital technology to design an upper limb prosthesis for the artist Luca Szabados; this progressed to an argumentative co-design development process that used prosthetic prototypes. A discussion of the relationship between disability and technology invites a critical philosophical approach to posthumanism, questioning the complex phenomena of a normalised society, phenomena that affect not only marginalised populations but also every human being in contemporary society (Barnes, 1996; Braidotti, 2013; Campbell, 2012; Goodley, 2014; Mallett and Runswick-Cole, 2014; Shildrick, 2015; Wolfe, 2009).

In their 1973 paper, Rittel and Webber suggested that complex and fragmented social challenges can be defined as 'wicked problems'. These complex and often ambiguous problems with high degree of uncertainty are difficult to define, solve, or even fully understand. Therefore, taming such problems with novel research approaches can defy the boundaries of standard analytical and rational processes (Rittel and Webber, 1973).
At our first project meeting, Luca questioned our research's initial intention; and invited many new questions to understand Luca's personal needs and interests. We clarified that Luca does not need nor wish to have a prosthesis. Based on her experience, she does not like to move around with a prosthesis object attached to her elbow stump. Luca's responses to the initial questions repositioned the initial theories at another point in the research framework inviting literature analysis on critical disability studies and questioning the initial normative view on prosthesis design. 'Disability is but one cultural artefact that signifies the "demise of humanism"' (Braidotti, 2013, p. 151), precisely because disability demands non-normative and anti-establishment ways of living. To use the language of McRuer (2006), disability crips what it means to be a human being.

Figure 1: Luca Szabados at her workshop. Photo by András Ladocsi.

The aim of our collaboration with Luca extended into generating new shared understandings of disability, and abilities by reflecting on argumentative and collaborative prototypes. An essential aspect of these prototypes is their intentional open-endedness and inexpensive production, designed primarily to facilitate discussions and debates. Luca adopted a meaningful role in the ecosystem of the discursive prototypes and thus reinforced her status as a person with assets rather than a person with a lack of ability (Manzini, 2015; Munro, 2016). The methodology adopted for this doctoral research thus enables an exploration of prosthesis design that is led by the tangible analysis of theoretical concerns. It engages in dialogue through co-design practice without the pressure of developing or commercialising a terminal design product. The prosthetic prototypes guided our reflections as a non-verbal modelling media and reflections on concepts of co-Ability. The role of prototypes encompassed not only the experimental and physical nature of the research but also presented links in the chain of knowledge development and carried evidence data.

Non-static and changeable entities in prototyping

The best way to understand the co-Ability phenomenon analysed in the research is by viewing the relational network that morphs and the changes in action generated by key elements within the continuously transactional activity. All the key players (biological and artificial) in this research considered as independent actors with agile and open collaborative actions. The designer researcher, a person with a disability, the digital manufacturing technology and the tangible artefact bring their own disciplinary perspectives on innovation and support the shared competencies in the network of collaboration. The interdependent network established by this research framework allows for divergence and changes in key aspects, aspects that are context-dependent and unstable over time. Posthuman studies advocate for an inclusive understanding of the network of interconnected elements and invite these elements to participate in a broader movement that addresses complex contemporary challenges, such as social policy, urban planning, healthcare, and environmental management. As Rosi Braidotti (2013) notes, the rapidly changing field of disability studies is emblematic of the posthuman predicament. In this research, I consider the knowledge-generating networks of four significant stakeholders to define four different principles of participation. Each physical element within the research frames a matrix of disciplinary knowledge and represents fragmented, novel, and complex issues affecting decision-making in prototyping. In the co-design approach used here, no single element possesses the independent ability to develop discursive prosthesis prototypes. The 'posthuman condition introduces a qualitative shift in our thinking about what exactly is the basic unit of common reference for our species, our polity and our relationship to the other inhabitants of this planet' (Braidotti, 2013, p. 2). The artificial and biological elements of the framework in relation, including the humans, as well as the digital technology and physical artefacts, are all interdependent actors in the network, and they all affect each other's activity even when they are not directly connected. This means that each of the elements in the network cannot generate new activity without considering the other contributing actors in the larger structure. Actor-network researchers such as Jim S. Dolwick (2009) and Bruno Latour (2007) propose to collectively view people, artefacts, and processes in socio-material political assemblies. In and upon the theory development, the prosthesis prototypes developed for this work were orientated as a basis of reflections, as 'object for discourse' that can 'talk back' in action through their physical presence (Mazé, 2007). A strong grounding in materiality and crafting through digital experience position the prototypes as a basis for reflection on design practice and research methods. This research has thus moved away from the classical linear supplier/consumer model for prosthesis development into the experimental Research through Design (RtD) model, in which variables situated in open research questions can controvert the predictive perspective of the initial hypothesis. The direct experience of a person with a disability in prototype testing offered internal critique from within. In human history, both disabilities and co-design methods possess a 'neverending' aspect that connects them in this morphological network, our understanding and approach to them has changed over time.

Figure2: Discussive prototypes in action. Photo by András Ladocsi.

The prosthesis prototypes were an essential part of this research, and they embodied a collection of mediated messages that address social, cultural, and technological issues.

> *Prosthesis simultaneously occupies the space of artificial limbs, metaphor, and discursive framework. (Kurzman, 2001, p. 375)*

The understanding of the term prosthesis encompasses 'a rich visual, political, and material vocabulary' that includes the ideas of 'prosthesis as an artificial limb," "prosthesis as aid" (i.e., aid to support an action), and 'prosthesis as metaphor' (i.e., an artificial body part that is 'integrated into the daily routines of the body') (Adams et al., 2015; Kurzman, 2001).

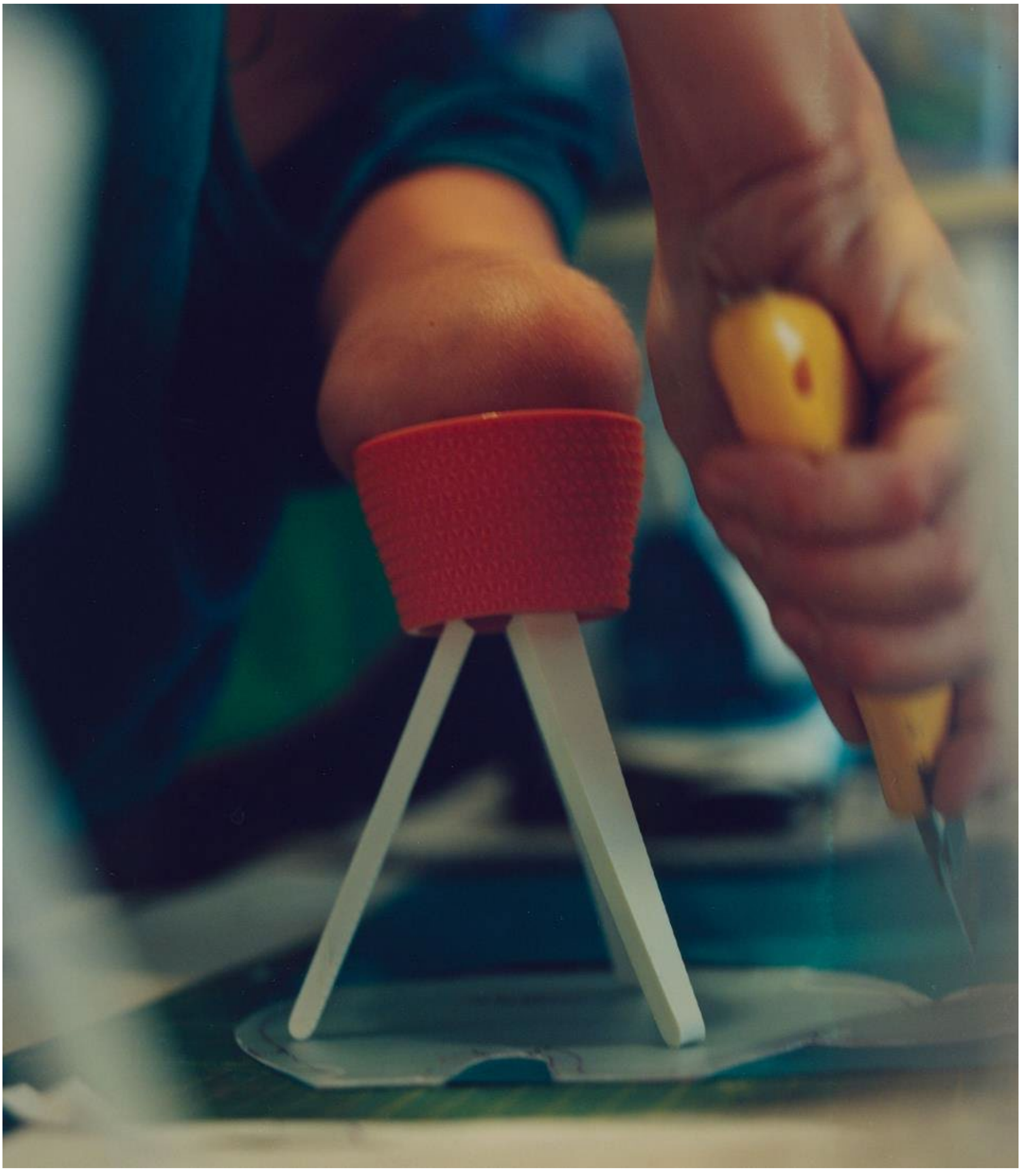


Figure 3: Luca Szabados testing the prototypes. Photo by András Ladocsi.

A bionormative model-led prosthetic design is an artificial interpretation of an anatomically intact limb. The denotative aspect of the prosthesis was challenged in the research by Luca's congenital disability and by contemporary disability studies. Rather than designing an artificial object to recreate a body part that has never been there, the intention was to develop an entity that could help to overcome certain environmental, personal, or social limitations. In this way, a prosthesis can be understood as any tool created in design history extending the boundaries of the human body. According to Malcolm McCullough (1998), a handheld device is typically considered a tool that requires active physical engagement and imagination to operate. This direct object–body connection is essential in this situated discursive research method, which provides concrete feedback on personal needs. In addition, the social context of disability encourages broader critical discussions. Finally, examining a prosthetic as a tool that integrates with the human body can contribute to the exploration of embodiment, which challenges the boundaries of what it means to be human (Carruthers, 2007; Dartnall, 2004; Dourish, 2001; Haraway, 1987; Shildrick, 2015).

Exploratory prototyping technology

During the computational design workflow for this research, I followed a designer-based iterative development in opposition to a self-organisational process of Morphogenetic Design (Hensel et al., 2012). For the iteration sequences, I used an applied surface CAD modelling technique. The 3D modelling process reflected on the situated discursive feedback from the 3D printed prototypes without inserting automated or generative proces with a parametric algorithm. For this research, I decided to use desktop 3D printers as the manufacturing technology within the large spectrum of possible rapid prototyping. These 'desktop robots' are game-changing devices in prototyping that practically melt a solid thermoplastic material (filament) and deposit it layer by layer in a specific design pattern in a process known as Fused Deposition Modelling. Compared with some traditional manufacturing processes, 3D printers offer more economical production by enabling the production of a model in a single process with a short build time, thereby offering the possibility for lightweight objects and a reduction of waste. Digital manufacturing allows for every piece of prototype to be differentiated in terms of size, proportion, and details while the general design and the purpose of the created object remain static. The economic and adaptive aspect of the desktop 3D printer is valuable not only in design development but also for future use for a larger audience with global filesharing local printing possibilities. Considering the material as the media in this process, there are also drawbacks to desktop printing. Working with a rigid material imposes limitations on build size and can have an impact on the accuracy of the part. Moreover, the size of the elements is constrained by the dimensions of an average desktop 3D printer's bed. However, micromechanical structures can influence the flexibility of a rigid material and improve its performance with regard to the body–object relationship. The work of design innovation firms such as Studio Bitonti-UNYQ and Nervous System, as well as individual designers such as Behnaz Farahi (2017), are leading inspirations in micromechanical structures for orthopaedic and prosthetic products. Unfortunately, desktop 3D printing technology has such physical limitations that prevent the creation of micro-sized and sophisticated geometry for the prototypes. Despite this limitation, to improve the body–object performance altering a material's geometrical configuration is still possible. I strategically selected geometries to showcase dynamic behaviour, such as enlarged one-ball rotational bearing gear, and flexible adaptive side pieces. In addition, the desktop printing process provides the opportunity to create an interlocking design that can be leveraged to produce a pre-assembled object capable of supporting certain bodily movements.

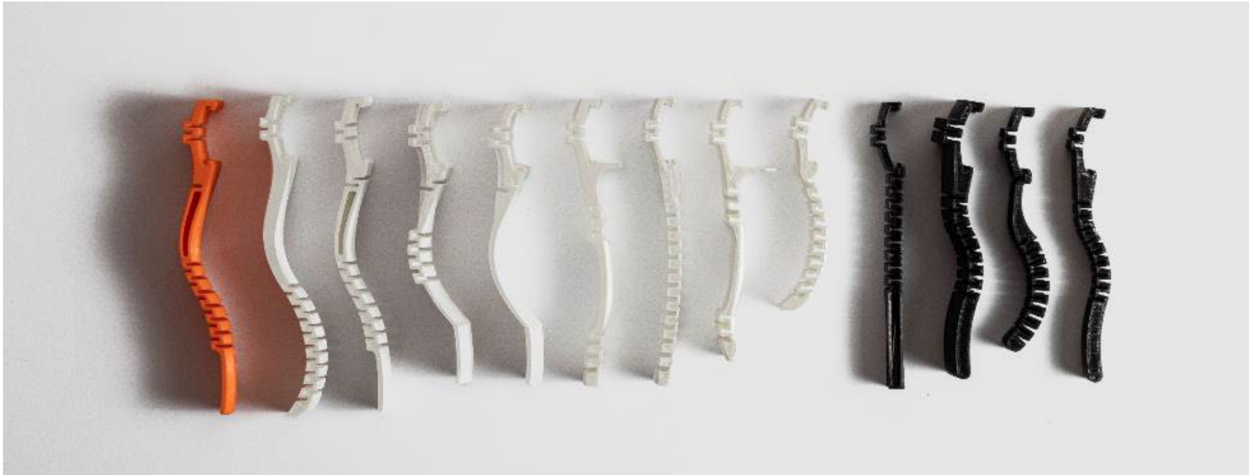


Figure 4: prototype iterations. Photo by Marcell Kazsik

The most important element of this designer-based iterative development with digital prototyping technology during the alteration process is the mutation of temporalities in 'material practice' with the resultant changes in the formation of 'participatory practice'. These alterations in the concept of 'becoming in the making' affects 'futurity' and the current and sublimed values as a cultural, historical, and political matter (Agre, 1997; Bell et al., 2005; Mazé, 2007; McCullough, 1998).

> *Within RtD, the researcher and the objects created are entwined and cannot be separated, establishing knowledge through this relationship.* (Isley and Rider, 2018)

Martin Heidegger argued that the ontological structure of the world unfolds through interactions, an idea supported by Paul Dourish (1999), who argued that the world is not given or something to be discovered but rather something that unfolds in situations. The 3D-printed real-world prototypes developed for this project were examined as the best-structured information source of the theory development (rather than text-based information data source as in other sciences). Visiting and revisiting the tangible real-world material scene as the research changed and developed required Luca's experienced nature of the specific movements in the context, and this involved a consideration of how subjective illusion adapts dynamics into the cortical motor-loop-specific movements. Ontologically, the prototypes developed for this work have a probe and reprobe material data structure with dynamics and uncertainty that trigger the domain of human experience. To improve the prosthesis prototypes developed the information gathered by the response to action-oriented touch and vision – senses that extend perception. The 'exploratory tool of touch and animated vision' in digital craft are considered the dominant parallel sensory modalities with which also a designer works. These two modalities are closely related to the (body) image and the (body) schema in knowing ourselves and detecting the material environment. These two modalities are closely connected to the (body) image and the (body) schema in self-recognition. Through these modalities, we recognise both consciously and unconsciously the world around us, therefore affecting the basics of our culture (Carruthers, 2007). The implicit and explicit representations of sensory understanding of ourselves and the material environment (biological, artificial) in the process of prototyping are a vital part of understanding co-Ability theory in relation to how we connect with our material environment. Margolin and Margolin (2002) have discussed that as the 'broader understanding of how to design for social need might be commissioned, supported, and implemented' when the 'population in need' is connected directly with 'design for development', the ideas are often borrowed from 'alternative technology movement, which has promoted low-cost technological solutions'. Recent years have seen designers attempting to develop solutions to a wide range of societal challenges. By incorporating the users' needs in the processes of design, workaround solutions can advance co-creation and co-production processes for innovation. In direct cooperation with Luca Szabados, we became partners in the design process, contributing our specific skills into the development process through discussions of Luca's lived experience. Interactive modalities in the prototypes were guided by Luca's personal sociopolitical needs and essential skills that are often implicit and non-verbal. The design process can mediate exploratory prototyping cycles of future possibilities with a 'plausible', 'possible', 'preferable', and 'probable' set of concepts of new social, economic, or political roles for all societies. Involving a person with a disability in research brings social sciences and critical philosophy in posthumanism into design discussions. Questions relating to how we might address issues for 'marginalised' populations invite a consideration of the historical foregrounding of complex phenomena of a normalised society affecting every human being (Barnes, 1996; Goodley et al., 2014; Gustavsson, 2009).

The methodological approach of the co-design framework

Understanding the dynamics of co-design was not a linear process, as it continued to evolve until the end of the research. Sanders and Stappers (2008) describe designers in the co-design method as facilitators in problem-seeking with the goal of bringing up new situations to move forward without a precise goal for a terminal problem solution. In co-design contexts, a designer's mental process is called a ‘neverending jagged line of opportunity-driven approach’ (Conklin, 2005). This constantly evolving process in the problem setting of social situations is influenced by time and progress. Therefore, it focuses on human aspects that are continuously evolving as well and attempts to align new challenges and environments with micro solutions. In this research, the co-design assemblage established the principle of knowledge by the four key players mentioned earlier. The four entities interacting on three different relational levels (layers of theories, competence and physical presentation) compass a micro-network articulating the theory development of co-Ability. The co-design case study method here situates the role of a designer not as an external expert but rather as a participant in the research (Cross, 1982; Höök et al., 2018; Tomico Plasencia, O. et al., 2012). Also considering the digital technology for co-creation in this project reflects on how data variables were mapped into the artefact while creating digitally crafted physical manifestations of the action-oriented data. The process was similar to a traditional crafting process, altered with a documentable data transfer between technological elements (computer, 3D printer machine) and humans. The process of transference between the visual and physical existence of the prototype alters the information data into a textualised code that controls the 3D printer's movements; this then produces the computed visual model and the physicalised prototypes, which are comprehensible to humans. After each printing session, the printed parts required hand-crafted post-production, which offered significant feedback through sight and touch as the physicalised real-world data were actively viewed and handled. Action-specific movements with interaction modalities (the animated vision and the exploratory tool of touch) enable a better understanding of the information manifested in real-world data of the tangible product (Ballard, 1991). The role of emergent knowledge in prototypes becomes the extended organ of physiology for the designer in the co-creation phases of digital manufacturing; we adapt our actions in response to detected information using these extended organs of physiology in the material world that exists beyond our body. It is not easy to transfer nonverbal knowledge when the format of sharing is text-based, it is implicit owing to its physical nature, and errors such as long printing hours render it explicit again. Therefore, it is essential to dwell on errors and difficulties to continuously understand the working procedures, as Richard Sennett states in 'The Craftsman' (2008). The particularity of the co-design activities with Luca provided directions to situative reflective discussions on and physical investigations of prototype artefacts. Prototypes presented a new synthesis of the ideas that we discussed, taking into account a special kind of aesthetic that could function as both a social symbol and political emblem for Luca. The visual appearance of the prototype carried a more profound, integrative argument on stigma and divergence from the negative perceptions of difference (deviance). As a matter of principle, the testing of the prototype centred exclusively on Luca's experiences while I was in charge of transforming Lucas's experiences into explicit wisdom so that they could be implemented into tangible objects. The action of use defined the shape of the prototypes. As Longmore (2003) argues, 'The disability perspective, the insights, experience, and expertise of people with disabilities, must inform research, producing new questions and generating new understandings. At the same time, academic researchers can help bring new rigour to the disability rights movement's analysis and activism'. The unusual prosthesis shape affected and placed its representation that oriented new perceptions of the prosthesis prototypes. The meaningful character of social action of the co-design process was invigorated by material reality. The tangible reality of the prototypes strengthens the objectivity of the interpretive paradigm of social reality in research.

Evidence data in artefacts

> *Different types of research method can provide different kinds of evidence which, when seen as a whole, can provide a 'rich picture' of the issue being investigated.* (Gray and Malins, 2004).

The narrative of co-Ability phenomenon is supported by evidence provided by the prosthesis prototypes. The representation of the data evidence appears mainly in illustrative drawings, 3D models, photographs, and 3D prints. Two data sets with different prototype functions are discussed below. The first focuses on supporting a flat surface, and the second is an attachable modular grip element.

Figure 5: Large number of prototypes. Photo by Márk Lakos

The exploration of the complexity of a social phenomenon of Luca's lived experience generated a large number of prototypes with various levels of execution. The prototypes do not communicate the designer's excellence in the power of care for disability. The artefacts consist of the contextual and relational ambiguity suggested by (Gaver et al., 2003): 'Contextual ambiguity can question the discourses surrounding technological genres, allowing people to expand, bridge, or reject them as we see fit. Relational ambiguity, finally, can lead people to consider new beliefs and values, and ultimately their own attitudes'. The discursiveness of the prototypes points to the viewer's affinity towards normative expectation by deliberately pursuing Luca's functional needs with a non-bionormative, non-human design (Mori et al., 2012).

The central theme for the primer prototypes

Together, we outlined those elements of Luca's routine for which a designed aid might improve her performance in her work. 'Disability is not a personal characteristic but is instead a gap between personal capability and environmental demand' (Verbrugge and Jette, 1994).

Supporting a flat surface on a table could serve Luca while working with a utility knife. Using a cutter is a daily short-term work-related task for Luca. Whereas the design for upper limb prostheses is most commonly associated with grasp movement (e.g., to enable one to hold a cup or grasp a doorknob), we identified with Luca that a simple mechanical tool to support something on a surface would be more useful (e.g., for holding paper in place while cutting). To produce a tool for such a simple task, it was not necessary to involve cybernetics or bioengineering, both of which are often associated with prosthesis developments. 'Efforts to improve prosthetics and orthotics resulted in a speciality that adopted scientific principles and engineering methodologies' (Tate and Pledger, 2003). Digital technology affected the production time and the production of the artefacts instead. The prototype components were developed with rigorous technical practice to eliminate the necessity for any external materials such as glue or screws; instead, the objects were designed to be assembled by interlocking.

Figure 6: Luca Szabados testing the prototypes; cutting with a cuttler. Photo by Andras Ladocsi

Figure 8: Modular element for card games. Photo by Renáta Dezső.

A secondary theme for the prototypes

Patterns for future predictions on other situations in which an artificial tool could be useful for short-term use appeared throughout the course of the research. Several short-term activities were considered in playful discussions, such as food preparation or holding a card pack in card games. In light of this, a new secondary theme of prototypes emerged; these would require adaption to the elbow stump and thus presented alternative modularity for further developments. The aesthetic outcome communicates the complexity of the subject from contrasting angles, and the modularity encourages the exploration of alternative strategies in additional design. The modular elements have a single ball as a rolling element that is locked into the central bearing bed.

Figure 9: prototypes and technical drawings at the dissertation defence. Photo by Màrk Lakos

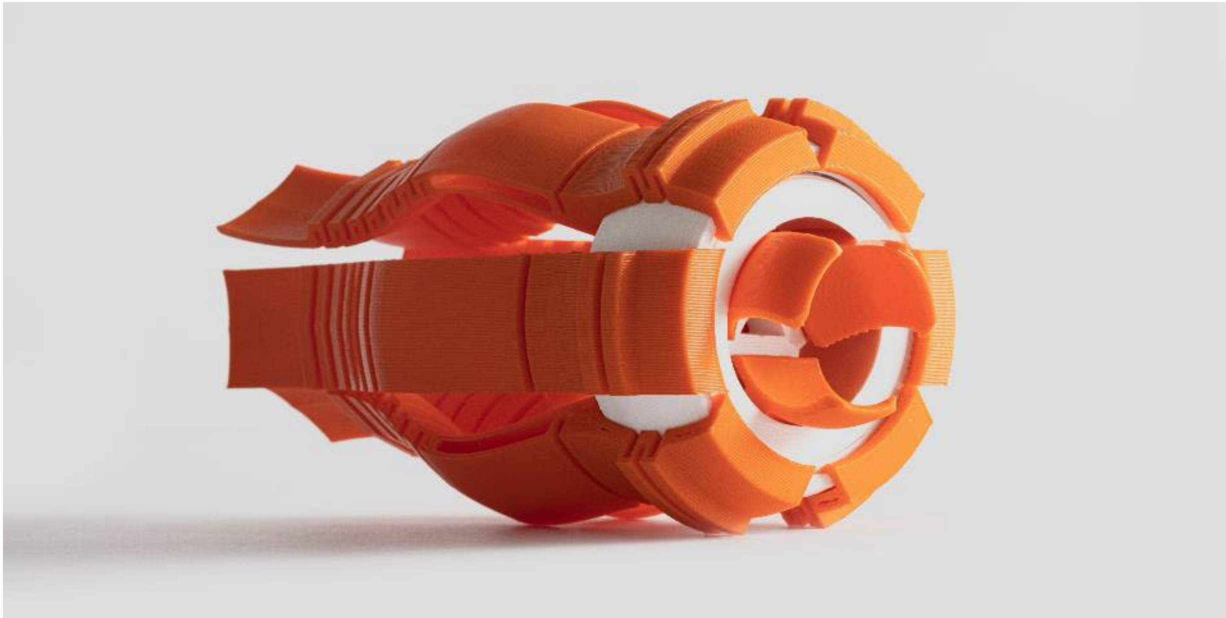


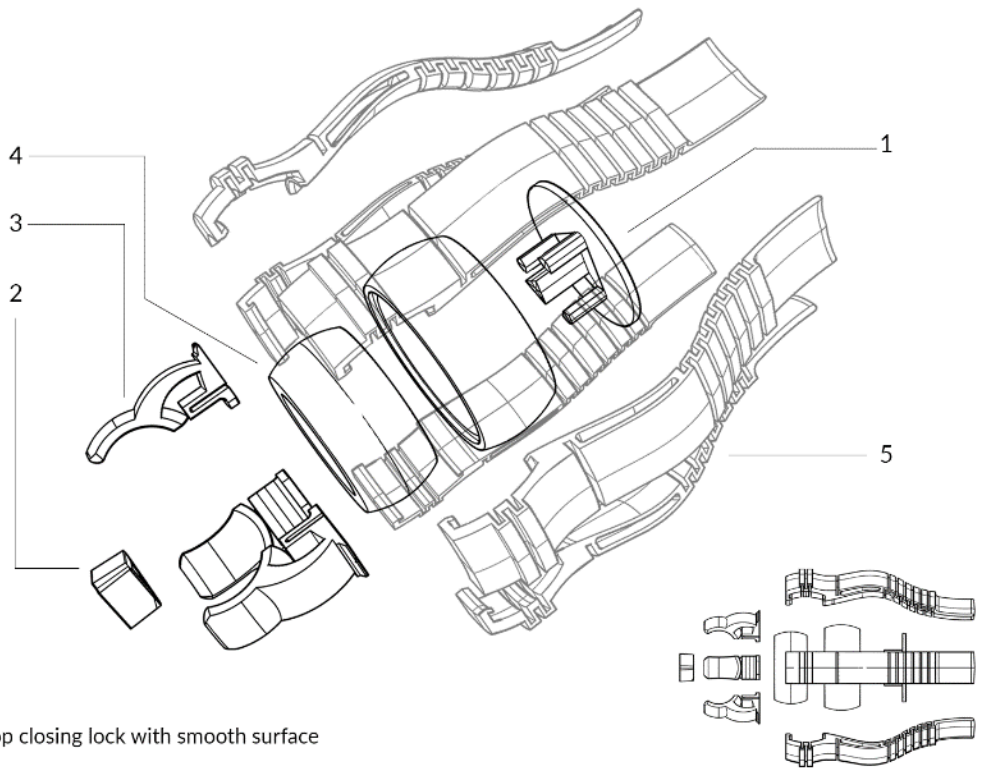
Figure 10: 3D-printed modular grip prototype. Photo by Marcell Kazsik

> *The more we examine our data from different viewpoints, the more we may reveal-or indeed construct their complexity.* (Coffey and Atkinson, 1996)

It is a challenge to adapt the design to an elbow stump shape that is constantly changing in movement, especially given the rigid nature of the material condition of Polylactic Acid Plastic (PLA) printed prototypes. Ideating from the double Gaussian curvature laser cutting wood technique, I modelled a flexible attachable element that could be clicked on to the central bearing bed. With this adaptive element, Luca could take the prosthesis on or off in a matter of seconds without much attention needed.

Figure 8: 3D-printed modular grip prototype. Photo by Marcell Kazsik

Figure 8: Objects designed to be assembled by interlocking. Photo by Marcell Kazsik



1. Top closing lock with smooth surface
2. Bottom locking element
3. Modular bearing bed with three interlocking elements
4. Central bearing element printed in one
5. 6 flexible side elements to be locked on the central bearing shape

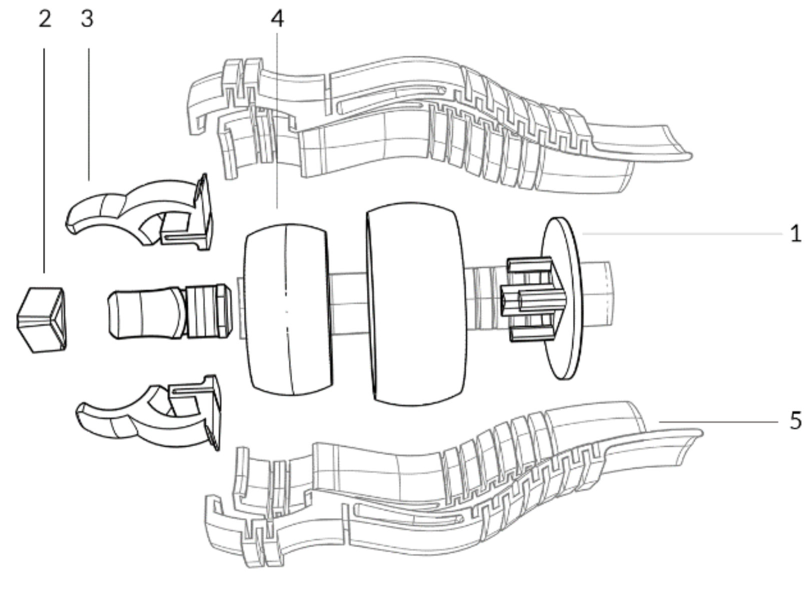


Figure 9: Exploded view of the central part of the modular model

To experiment with the idea of modularity, two directions were created. One is a general autoclip forceps; the second is a large mouth clip for card games, which was made especially at Luca's request.

Research through prototypes and conclusion on theory development

The empirical study for the theory development in this doctoral research includes an exploration of RtD methods (i.e., experimental research based on a case study) (Buchanan, 2007; Gaver, 2012; Koskinen et al., 2012; Zimmerman et al., 2007). Designing an aesthetically pleasing artefact or developing prototypes that lead to market-ready products was not the study's primary aim. Rather, focused research produced a chain of prototypes that supported the theory development and represented the thesis. As it has been argued elsewhere, 'The development of prosthesis created with collaborative design practice should not target only methods of solving design problems, but also informal and social interactions in posthuman collection' (Dezső, 2019). According to Visser (2006), an expression such as 'design is not problem-solving' is an abbreviated form of the idea that 'many design tasks constitute no problem-solving tasks for the designers in charge of these tasks'. Visser goes on to note that

> *The focus on 'real design' points toward design as performed in a designer's usual working situation—rather than in artificially restricted conditions, such as laboratory experiments. (Visser, 2006)*

The research framework is built upon the situated design perspective introduced by Lave and Wenger in 1991. This approach recognises the intricate interplay between the human context and the design process, a concept further developed by Terry Winograd in 1996. The research applies a situated approach that examines the interaction between the object and the body, drawing upon Schön's ideas of reflective practice, reflection-in-action, and knowing-in-action. Meaningful variation in secondary data present in the prototypes of this single case study, which provided two groups of datasets to be physicalised fast-prototyping. Transforming the view of 'forces of production', the tangible material conditions of the prototypes proved to be a reliable instrument for mapping out and building up a view of co-Ability. Entering into 'relations of production', the argumentative nature of discursive prototypes entails a better understanding of human-centred normative visions of our world. These prototypes are argumentative in nature, as they lay out the viewer's nonverbal, normative expectations and invite discussion. Prosthetic artefacts that combine contextual and relational ambiguity question the' discourses surrounding technological genres, allowing people to expand, bridge, or reject them as they see fit. According to Gaver et al. (2003), relational ambiguity can prompt individuals to reconsider their beliefs and values, leading to shifts in attitudes. Drawing on Carroll and Kellogg's (1989) argument, prototypes can be seen as a "theory nexus", encompassing the philosophical, functional, aesthetic, and social dimensions of design. I also agree with Kettley et al. (2015) that as design research becomes more involved in areas that affect our wellbeing, a structured approach can support researchers in their work.

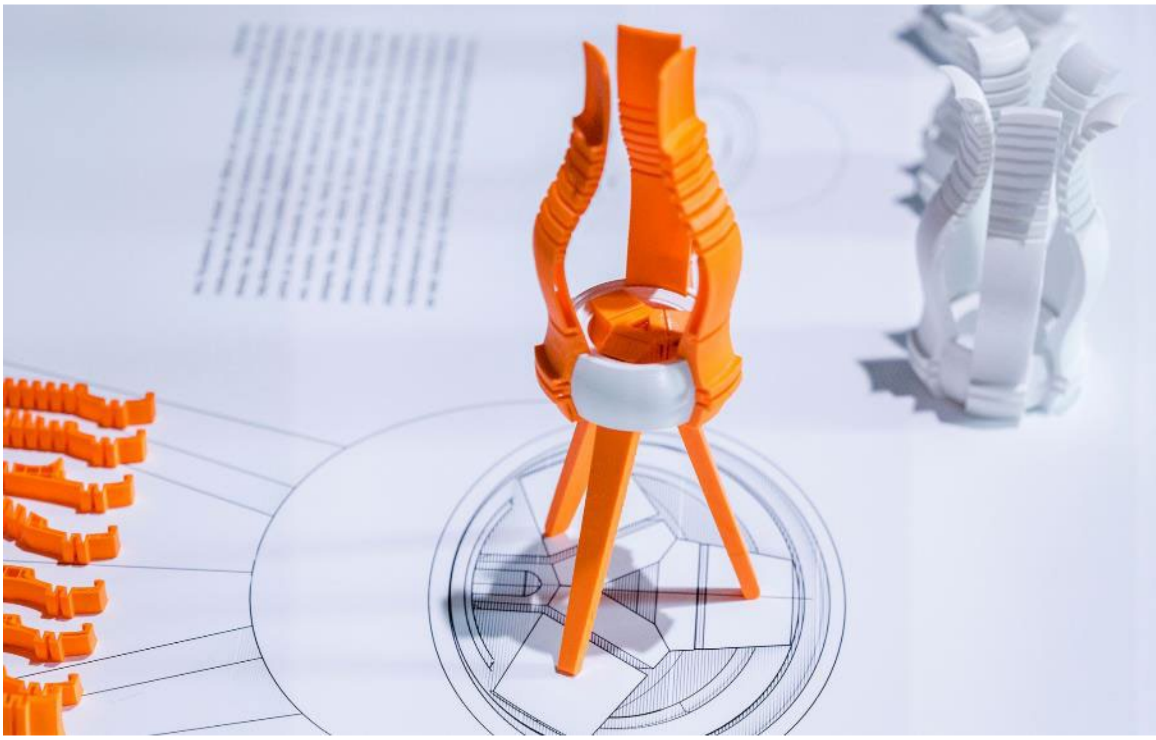


Figure 10: 3D-printed prototypes and technical drawings. Photo by Màrk Lakos

The analysis reveals that this research generated a corpus of data on design artefacts that enables one to engage with questions relating to the intersection of co-Ability and design. In light of the rhetorical approach, repeatedly creating and refining initial prototypes with multiple probes and reprobes until the prototype data become familiar is a necessary step toward action orientation. The practical action required in this context is represented in the prototypes. The 'rigour in research' is embedded in the chain of reasoning that emerged during the process documented in the prototypes (Biggs and Büchler, 2007).

Figure 11: 3D-printed prototypes. Photo by Màrk Lakos

The appearance of a prosthetic and its alignment with the perceiver's affinity with non-bionormative prostheses, which intentionally avoid a human-like appearance are interconnected. As Gray and Malins (2004) argue, 'The context in which the evidence [i.e. the artefact] is being used is important, as what counts as evidence in one particular context may be unacceptable in another'. To quantitatively validate the concerns in this paper, the research method does not necessarily need to be repeated, but the artefact/prototypes could be reproduced with further open-ended development.

The social design discussed in this paper focused on Design for Social Innovation and Sustainability (DESIS), a strand of design practice with objectives and processes that aim to lay the foundations for social change. The research focused on the relational network of elements while the attention shifted to instigating change for any community. To achieve sustainable social change, the paper suggests altering the patterns of what is considered "normal" by fostering new perspectives that take into account co-Ability. The term refers to considering the idea of 'ability' as a distributed phenomenon rather than an individualised trait. To trespass the normative vision of individual traits and promote shared competence in many occurring everyday life contexts could creatively and innovatively challenge human-centred societal issues with a high degree of uncertainty.

Overall, the paper emphasises the role of prototypes in promoting social change and offers insights into how design practices can be used to create more equitable and inclusive communities.

References

Adams, R., Reiss, B., Serlin, D. (Eds.), 2015. Keywords for Disability Studies. NYU Press.

Agre, P.E., 1997. Computation and Human Experience. Cambridge University Press, New York, NY, USA.

Ballard, D.H., 1991. Animate vision. Artificial Intelligence 48, 57–86. https://doi.org/10.1016/0004-3702(91)90080-4

Barnes, C., 1996. Disability and the Myth of the Independent Researcher. Disability & Society 11, 107–112. https://doi.org/10.1080/09687599650023362

Bell, G., Blythe, M., Sengers, P., 2005. Making by Making Strange: Defamiliarisation and the Design of Domestic Technologies. ACM Trans. Comput.-Hum. Interact. 12, 149–173. https://doi.org/10.1145/1067860.1067862

Biggs, M.A.R., Büchler, D., 2007. Rigor and Practice-based Research. Design Issues 23, 62–69. https://doi.org/10.1162/desi.2007.23.3.62

Braidotti, R., 2013. The Posthuman, 1 edition. ed. Polity, Cambridge, UK ; Malden, MA, USA.

Buchanan, R., 1992. Wicked Problems in Design Thinking. The MIT Press, Design Issues 8, 5–21. https://doi.org/10.2307/1511637

Campbell, F.K., 2012. Stalking ableism: Using disability to expose "abled" narcissism, in: Disability and Social Theory: New Developments and Directions. pp. 212–230. https://doi.org/10.1057/9781137023001

Carroll, J.M., Kellogg, W.A., 1989. Artifact As Theory-nexus: Hermeneutics Meets Theory-based Design, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '89. ACM, New York, NY, USA, pp. 7–14. https://doi.org/10.1145/67449.67452

Carruthers, G., 2007. Types of body representation and the sense of embodiment. Consciousness and Cognition 17, 1302–1316.

Coffey, A.J., Atkinson, P., 1996. Making Sense of Qualitative Data: Complementary Research Strategies, 1st edition. ed. SAGE Publications, Inc, Thousand Oaks.

Conklin, J., 2005. Wicked problems and social complexity. CogNexus Institute.

Cross, N., 1982. Designerly ways of knowing. Design Studies, Special Issue Design Education 3, 221–227. https://doi.org/10.1016/0142-694X(82)90040-0

Dartnall, T., 2004. We Have Always Been . . . Cyborgs. Metascience 13, 139–273. https://doi.org/10.1023/B:MESC.0000040914.15295.0e

Dezső, R., 2019. Co-Ability Practices. Proceedings of the 2019 8th biannual Nordic Design Research Society (Nordes) conference at Aalto University, Finland 0.

Dolwick, J.S., 2009. `The Social' and Beyond: Introducing Actor-Network Theory. Journal of Maritime Archaeology 4, 21–49. https://doi.org/10.1007/s11457-009-9044-3

Dourish, P., 2001. Where the Action Is: The Foundations of Embodied Interaction, in: Where the Action Is: The Foundations of Embodied Interaction. The MIT Press, p. pp.-256.

Dourish, P., 1999. Embodied interaction: Exploring the foundations of a new approach to HCI.

Gaver, W.W., Beaver, J., Benford, S., 2003. Ambiguity as a resource for design, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '03. Association for Computing Machinery, New York, NY, USA, pp. 233–240. https://doi.org/10.1145/642611.642653

Goodley, D., 2014. Dis/ability Studies: Theorising disablism and ableism, 1 edition. ed. Routledge, New York.

Goodley, D., Lawthom, R., Runswick Cole, K., 2014. Posthuman disability studies. Subjectivity 7, 342–361. https://doi.org/10.1057/sub.2014.15

Gray, C., Malins, J., 2004. Visualising Research: A Guide to the Research Process in Art and Design. Routledge, Aldershot, Hants, England ; Burlington, VT.

Gustavsson, A., 2009. The role of theory in disability research -springboard or strait-jacket? Scandinavian Journal of Disability Research 6, 55–70. https://doi.org/10.1080/15017410409512639

Haraway, D., 1987. A Manifesto for Cyborgs: Science, Technology, and Socialist Feminism in the 1980s. Australian Feminist Studies 2, 1–42. https://doi.org/10.1080/08164649.1987.9961538

Hensel, M., Menges, A., Weinstock, M., 2012. Morphogenesis and Emergence. pp. 160–164.

Höök, K., Caramiaux, B., Erkut, C., Forlizzi, J., Hajinejad, N., Haller, M., Hummels, C.C.M., Isbister, K., Jonsson, M., Khut, G., Loke, L., Lottridge, D., Marti, P., Melcer, E., Müller, F.F., Petersen, M.G., Schiphorst, T., Segura, E.M., Ståhl, A., Svanæs, D., Tholander, J., Tobiasson, H., 2018. Embracing First-Person Perspectives in Soma-Based Design. Informatics 5, 8. https://doi.org/10.3390/informatics5010008

Isley, C.G., Rider, T., 2018. Research-Through-Design: Exploring a design-based research paradigm through its ontology, epistemology, and methodolog. DRS Conference Papers. https://doi.org/10.21606/drs.2018.263

Kettley, S., Bates, M.I., Kettley, R., 2015. Reflections on the heuristic experiences of a multidisciplinary team trying to bring the PCA to participatory design (with emphasis on the IPR method), in: UbiComp/ISWC'15 Adjunct. https://doi.org/10.1145/2800835.2807946

Kurzman, S.L., 2001. Presence and Prosthesis: A Response to Nelson and Wright. Cultural Anthropology 16, 374–387. https://doi.org/10.1525/can.2001.16.3.374

Latour, B., 2007. Reassembling the Social: An Introduction to Actor-Network-Theory, 1st edition. ed. Oxford University Press, Oxford.

Leach, N., Farahi, B. (Eds.), 2017. 3D-Printed Body Architecture, 1st edition. ed. Wiley, Oxford.

Longmore, P.K., 2003. Why I Burned My Book and Other Essays on Disability. Temple University Press, Philadelphia.

Mallett, R., Runswick-Cole, K., 2014. Approaching disability: Critical issues and perspectives, Approaching Disability: Critical Issues and Perspectives. https://doi.org/10.4324/9781315765464

Manzini, E., 2015. Design, When Everybody Designs: An Introduction to Design for Social Innovation. The MIT Press, Cambridge, Massachusetts.

Margolin, V., Margolin, S., 2002. A "Social Model" of Design: Issues of Practice and Research. Design Issues 18, 24–30. https://doi.org/10.1162/074793602320827406

Mazé, R., 2007. Occupying Time: Design, technology, and the form of interaction. Axl Books, Stockholm.

McCullough, M., 1998. Abstracting Craft: The Practiced Digital Hand. MIT Press.

McRuer, R., Bérubé, M., 2006. Crip Theory: Cultural Signs of Queerness and Disability. NYU Press, New York.

Mori, M., MacDorman, K.F., Kageki, N., 2012. The Uncanny Valley [From the Field]. IEEE Robotics Automation Magazine 19, 98–100. https://doi.org/10.1109/MRA.2012.2192811

Munro, T., 2016. Co-design: From Problem Solving to Strength-Based Re-authoring in Social Design, in: DRS 2016 Design + Research + Society Future–Focused Thinking. Design Research Society, Brighton, UK, pp. 2221–2240. https://doi.org/10.21606/drs.2016.271

Rittel, H.W.J., Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy Sci 4, 155–169. https://doi.org/10.1007/BF01405730

Sanders, E., Stappers, P.J., 2008. Co-creation and the New Landscapes of Design. CoDesign 4, 5–18. https://doi.org/10.1080/15710880701875068

Sennett, R., 2008. The Craftsman. Yale University Press.

Shildrick, M., 2015. "Why should our bodies end at the skin?": Embodiment, boundaries, and somatechnics. Hypatia 30, 13–29. https://doi.org/10.1111/hypa.12114

Tate, D.G., Pledger, C., 2003. An integrative conceptual framework of disability: New directions for research. American Psychologist 58, 289–295. https://doi.org/10.1037/0003-066X.58.4.289

Tomico Plasencia, O., Winthagen, V.O., van Heist, M.M.G., 2012. Designing for, with or within: 1st, 2nd and 3rd person points of view on designing for systems. Presented at the 7th Nordic Conference on Human Computer Interaction: Making Sense Through Design., Association for Computing Machinery, Inc, Copenhagen, Denmark, pp. 180–188. https://doi.org/10.1145/2399016.2399045

Verbrugge, L.M., Jette, A.M., 1994. The disablement process. Soc Sci Med 38, 1–14.

Visser, W., 2006. The cognitive artifacts of designing (Book, 2006) [WorldCat.org]. LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS, Manhattan, NJ.

Wolfe, C., 2009. What Is Posthumanism? University of Minnesota Press.

Renata Dezso

Renata is a designer and researcher at Moholy-Nagy University of Art and Design in Budapest, Hungary. Her doctoral research, entitled 'co-Ability; Aligned arguments for the dissolution of a human "centre"', was successfully defended in 2022. Renata specialises in utilising the Research through Design methodology to generate knowledge and understanding about the world, with a particular interest in exploring the intersection of digital and material craft, transformative design&science. She has developed a diverse portfolio of design works that includes social design, critical interventions, and explorations of emerging technologies with design practices. Renata strongly believes that the choices people make in their daily lives have the power to shape the world around them and advocates for creating new frameworks for understanding the world to promote more sustainable and equitable ways of living. In recognition of her work, she received the European Disability Forum (EDF) and ORACLE Award in 2020 and the Gillo Dorfles First Prize in the Trieste Contemporanea Contest in 2022.

Uncovering Tacit Needs through Prototyping: Designing Post-Harvest Storage Solutions for Marginal Farmers in India

Agnivesh Sharma, Indian Institute of Technology, Bombay, India
Nishant Sharma, Indian Institute of Technology, Bombay, India

Abstract

Agriculture is the most important occupation for most Indian families. It is a vital sector in India's economy, contributing 16% to the Gross Domestic Product and 10% to total exports. India is a leading producer of wheat, rice, pulses, and spices. However, there is a significant gap between agricultural production and storage capacity, leading to food waste and uneven availability of food grains. This problem is particularly acute for marginal farmers who cannot afford storage facilities. To address this issue, a participatory design study was conducted with marginal farmers to gain insights and aspirations for designing affordable and mobile storage solutions. The participatory design approach involved the active participation of farmers in the design process, using prototypes and mockups created using available materials. The mockups and prototypes were used as a medium for the farmers to express their ideas, problems, and solutions related to post-harvesting and storage. This process played a crucial role in gaining a deeper understanding of the farmers' needs from their perspective, and helped to design affordable and mobile storage space for marginal Indian farmers. The research was an essential step towards improving the storage capacity for marginal Indian farmers, reducing food waste, and ensuring a more efficient storage of food grains. The use of participatory design approach allowed a more tangible and practical approach to understand the farmers' requirements and design solutions accordingly.

Participatory Design; Agriculture; Co-creation; Farmers; Design Research

Agriculture is a major source of livelihood in India, with 70% of rural households depending on it for their livelihood. 82% of farmers in India are small and marginal. Agriculture is a significant contributor to the Indian economy, accounting for 16% of GDP and 10% of exports. India has a large amount of arable land, with over 60% of the (NABARD 2008) country's land area being suitable for agriculture. Indian agriculture has seen significant growth in recent decades. However, the sector still faces several challenges such as low productivity, lack of access to credit, and inadequate infrastructure. The government has implemented various policies and schemes to address these issues and promote the growth of the agriculture sector. The National Mission on Sustainable Agriculture (Kishore 2018) and the Pradhan Mantri Fasal Bima Yojana are some examples of such schemes. Despite the challenges, agriculture remains a crucial sector for India's economy, providing employment and food security for millions of people. India is the world's largest producer of pulses, rice, wheat, spices, and spice products, and is the second-largest in total farm outputs (Agarwal, 2009). In 2017-2018, total food grain production was estimated at 275 million tonnes. India is the largest producer of around 25% of global production, accounts for around 27% of world consumption, and imports around 14% of pulses in the world. India is also the second leading producer of various crops such as rice, wheat, sugarcane, cotton, and groundnuts. Additionally, it is the second largest producer of fruits and vegetables, making up for 10.9% and 8.6% of global fruit and vegetable production respectively. Agriculture in India is heavily dependent on monsoon rainfall, as 68% of farmers are marginal farmers who rely solely on rain, river, and canal irrigation (Krishna 2004). The country's agriculture sector also faces challenges such as low productivity, lack of access to credit, and inadequate infrastructure.

There are several reasons for post-harvest losses in India, including the lack of modern grain storage facilities, inadequate market infrastructure,(Somashekhar 2014) and fragmented supply chains. The lack of modern grain storage facilities means that food grains are often stored in suboptimal conditions, which can lead to spoilage and waste. Inadequate market infrastructure, such as poor transportation and logistics, also makes it difficult to get food grains to consumers in a timely and cost-effective (Parwez 2014) manner. Finally, fragmented supply chains can make it challenging to coordinate the movement of food grains from producers to consumers, further exacerbating the problem of food loss. According to recent reports, India has experienced a significant loss of food grains in storage facilities since 1997. The total loss is estimated to be 6,035,000 metric tons, with 0.5 million metric tons of rice and 35 metric tons of wheat being wasted specifically. This is a concerning issue that highlights the need for more efficient storage and distribution systems in order to prevent such wastage in the future. In addition, these numbers speak to the importance of addressing food security and reducing food loss as a crucial aspect of sustainable development.

Rural farmers in India use traditional knowledge (Tara 2015) to construct grain storage structures. By standardizing this traditional knowledge using modern methods, storage losses can be minimized. The ongoing growth in annual agricultural production (Sayyad 2016) in India is creating a growing demand for more storage space to reduce wastage. Agricultural exports from India are increasing by 20%–25% annually and it has emerged as one of the largest exporters of fruit and vegetables, driving growth in high-quality demand for warehousing. Basavaraja (H. Basavaraja 2007) studied that storage losses account for about 35.8% of total post-harvest losses in rice and 33.52% in wheat. Establishing small-size cold storage units in production centers would help to reduce these storage losses. Studies shows that (Shweta 2014) the net production of food grains and the per capita availability of food grains in India and found that even though food grain production is increasing, the per capita availability of food grains is decreasing due to gaps in storage. Storage infrastructure is a critical issue in the Indian agriculture sector, and addressing this issue is essential for increasing productivity and reducing food waste. Participatory design research is a promising approach that can be used to involve farmers and other stakeholders in the design and implementation of storage facilities, leading to solutions that are tailored to the specific needs and constraints of the local community.

This study uses participatory research methods to understand the post-harvesting and storage problems faced by marginal farmers in a specific place. The study involves 12 farmers divided into three groups, with 4 farmers in each group. The farmers are first asked to think about the post-harvesting problems and then the need for participatory research is explained to them. A semi-structured interview is conducted to gather information and insights.In the second stage, farmers are asked to design solutions to solve the storage problems with the given materials. They use paper models to create multiple versions of solutions as it allows them to quickly make changes and evaluate different options. This approach allows farmers to be actively involved in the process and engage in conversation about the design. The use of paper models also allows for a continuous challenge and change model of the design, which can help to identify the best solutions. This study highlights the importance of involving farmers in the research process and using participatory research methods to understand their perspectives on post-harvesting and storage problems. It also shows the potential of using paper models as a tool for designing solutions to solve storage problems. The designer gained valuable insights from the mockups and prototypes created by farmers during the participatory design process. These prototypes allowed the designer to understand the farmers' perspectives on post-harvesting and storage problems, and identify potential solutions. The farmer's prototypes and mockups were used as a starting point to design a more detailed and refined solution for the problem of storage space.

The objectives of this study are three-fold:

1. **To uncover farmers' tacit needs and knowledge**: The study aims to uncover the implicit and deeper understanding of the post-harvesting and storage problems faced by marginal farmers. This knowledge is usually not easily accessible and is acquired through years of experience and practice. It is important (Sanders 2012) to understand these tacit needs and knowledge in order to design a solution that is appropriate and effective.
2. **To explore the different best possible solutions based on farmers' knowledge and experience**: The study aims to explore different solutions to the storage problem that are based on the farmers' knowledge and experience. By involving farmers in the design process, the study aims to identify the best possible solutions that are practical, cost-effective and tailored to the specific needs of the community.
3. **To provide a clear roadmap for the designer to design a suitable concept:** The study aims to provide a clear roadmap for the designer to design a suitable concept for the storage problem. By uncovering farmers' tacit needs and knowledge and exploring the different best possible solutions, the study aims to provide the designer with a clear understanding of the problem and the necessary information to design an appropriate solution.

Methodology

The methodology structure of this study includes several key steps to uncover farmers' tacit needs and knowledge, explore the different best possible solutions, and provide a clear roadmap for the designer to design a suitable concept for the problem of post-harvesting storage space.

1. **Interviews:** The study starts with conducting semi-structured interviews with the farmers to gather information and insights about the post-harvesting and storage problems. The interviews are conducted with a set of random questions that are asked according to the previous answers and based on (Boyce 2006) some new insights from the literature. These interviews provide an understanding of the farmers' perspectives on the problem and their current practices. Interviews play a critical role in the design process by providing valuable information and insights about the problem, user needs, and current practices. They allow designers to gain a deeper understanding of the context and environment in which the problem exists, and the perspectives and experiences of the users.

2. **Field study:** The study also includes a field study to gather more information about the context and environment in which the problem exists. This can include observing the current storage practices, examining (Teegavarapu 2008) the physical environment, and gathering data on the local climate, culture, and economic conditions. Field studies allow designers to observe the problem first hand, which can provide a deeper understanding of the problem and potential solutions. They also allow designers to identify opportunities and constraints in the environment, this information can inform the design process and help to create a more effective solution.

3. **Brainstorming session:** After the interviews and field study, a brainstorming session is conducted with the farmers to identify the major problems related to post-harvesting. This session provides an opportunity for farmers to share their knowledge and experience and

identify the key issues that need to be addressed in the design process. The brainstorming session also allows (sutton 1996) farmers to think creatively and come up with new ideas and solutions that may not have been considered otherwise. This lead to a more comprehensive and effective solution that takes into account multiple perspectives and experiences. This is an effective way to gather ideas from a group of people and generate a wide range of potential solutions to the problem at hand.

4. **Participatory design with farmers:** The study includes a participatory design process where farmers are actively involved in the design process. They are asked to design their solutions to solve the storage problems with the given materials. Paper models are used as a tool to create multiple versions of solutions. This approach allows farmers to be actively involved in the (Sanders 2012) process and engage in conversation about the design. The use of paper models also allows for a continuous challenge and change model of the design, which can help to identify the best solutions.

5. **Designing final solution:** Using insights gained from research, the designer creates a detailed solution for the storage space problem. This solution takes into account the insights gathered from the interviews, field study, brainstorming session, and participatory design with farmers. The solution is designed to be practical, cost-effective, and tailored to the specific needs of the community.

Below figure shows the double diamond process (Council 2016) and participatory design used in the define and develop phases. During the Define phase, participatory design methods such as user interviews, focus groups, and co-creation workshops used to understand the needs and requirements of the intended users. By combining participatory design with the Double Diamond process, designers can ensure that the final solution is farmer-centered and meets the needs of the intended users.

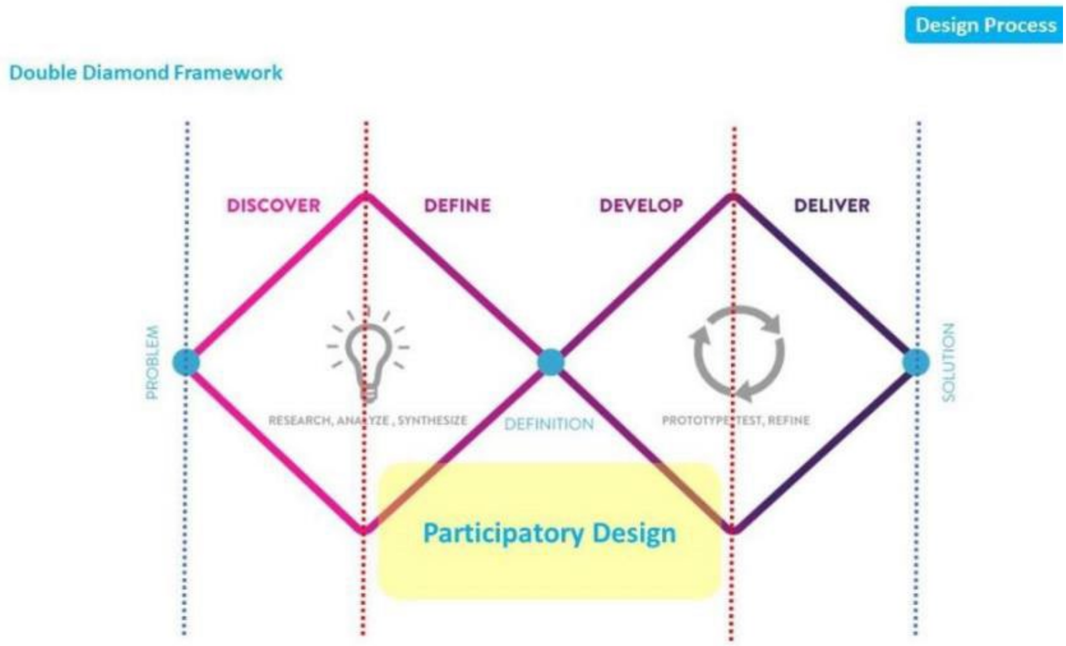


Figure 1: Double Diamond Process with Participatory Design approach.

One of the key benefits of participatory (Sanders 2012) research is that it can help to uncover tacit needs, or needs that are not explicitly stated or known by the research subjects. This is because the active participation of the subjects in the research process can allow researchers to gain a deeper understanding of their perspectives, experiences, and needs, which can lead to the identification of unarticulated needs. All research techniques in use today for exploring people's experiences fall into one of three categories- what people say, do, or make; or they fall into the area of overlap between the categories.

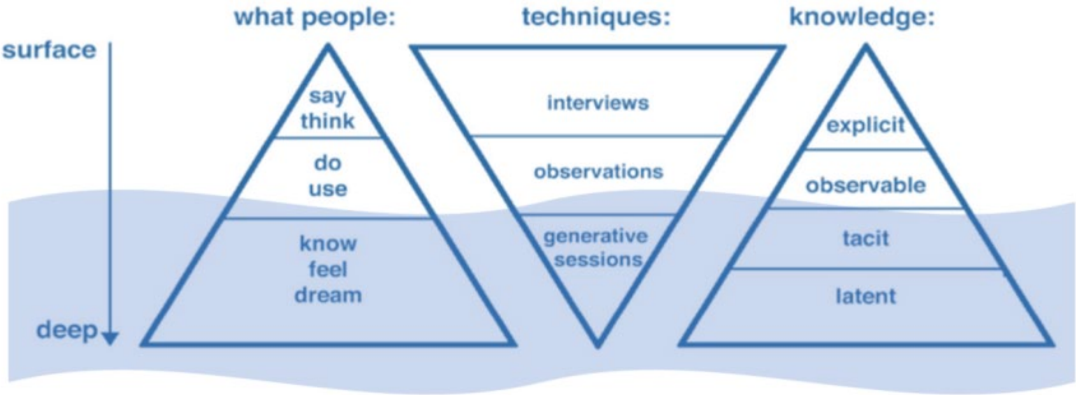


Figure 2: Method that study what people say, do and make help access different levels of knowledge.

(Source: Convivial Toolbox: Generative Research for the Front End of Design.)

Overview of Indian Farmer, Holdings, Production, and Storage Capacities

Different segment of farmers in India

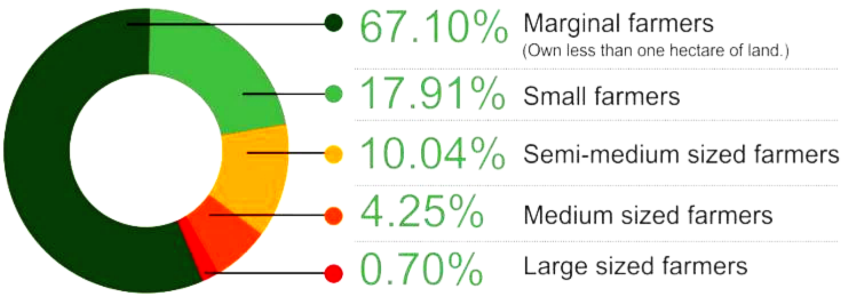
There are several different segments of farmers in India. The table given below shows that, there is 138.348 Million total number of farmers, out of which 0.23 million have Institutional farm holdings, 19.51 Million Joint (Bhavan 2012) Holdings, and 118.59 Million Individual farm holdings. In India 67% of farmers are Marginal, 18 % small farmers, and only 1% large farmers.

Area: in '000' Ha   Number: '000' Units

Sr No	Size of holding	Individual Holding		Joint Holding		Institutional Holding		Total Holding		%
	Number	Number	Area	Number	Area	Number	Area	Number	Area	
1	Marginal (0-1 Ha)	80125	30807	12563	5004	138	45	92826	35908	67%
2	Small (1-2 Ha)	21354	30407	3392	4790	33	47	24779	35244	18%
3	Semi medium (2- 4 Ha)	11684	31583	2185	6048	26	73	13896	37705	10%
4	Medium (4-10 Ha)	4738	27130	115	6567	21	132	5875	33828	4%
5	Large (10 Ha & above)	691	10874	262	4788	20	1245	973	16907	1%
All Classes		118592	130854	19518	27196	239	1542	138348	159592	100%

Table 2: Number and Area of holding by farmer size group. (Source: Agriculture Census Report 2011)

Marginal farmers in India



(Source: Agriculture Census 2010-11)

Most of the marginal farmers have very less or no space for storage. They are dependent on the Government warehouse and repositories as they are not wealthy enough to afford their own storage space. Hence the marginal farmers are targeted to conduct participatory research to understand problems related to post-harvesting and design affordable storage space.
The storage capacity available with the major player in Indian agricultural warehousing Food Corporation of India was 9.22 MT in Punjab, (Bhavan 2012) followed by 5.9 MT in Uttar Pradesh, 4.81 MT in Andhra Pradesh and 3.22 MT in Haryana whereas food grain production in Punjab was 28.54 MT in 2012 and Uttar Pradesh was 50.745 MT in 2012.

state / UT	Production 2012-13	storage	Utilization %	state / UT	Production 2012-13	Storage	Utilization %
Andhra Pradesh	18.663	4.81	69.1	Mizoram	0.0418	0.03	92.3
Arunachal Pradesh	0.364	0.02	50	Nagaland	0.5791	0.03	75.8
Assam	5.2806	0.28	50.9	Odisha	8.0088	0.61	67.3
Bihar	15.94	0.72	56.9	Punjab	28.543	9.22	81.7
Chhattisgarh	7.6436	1	56.6	Rajasthan	18.368	2.59	92.5
Goa	0.1318	0.02	60	Sikkim	0.106	0.01	54.5
Gujarat	7.0562	0.86	80.4	Tamil Nadu	5.5928	1.02	74.1
Haryana	16.226	3.22	88.6	Tripura	0.7252	0.05	83.3
Himachal Pradesh	1.4807	0.04	40	Uttar Pradesh	50.745	5.9	49.9
Jammu & Kashmir	1.8319	0.14	69.5	Uttarakhand	1.8277	0.2	62.9
Jharkhand	4.5575	0.13	63.4	West Bengal	16.547	1.09	52.9
Karnataka	10.863	0.91	90.2	A & N Islands	0.0224	0	0
Kerala	0.5118	0.54	76.7	Delhi	0.0903	0.37	63.5
Madhya Pradesh	23.69	0.74	80.5	D & N Haveli	0.0344	0	0
Maharashtra	10.973	2.31	70.6	Daman & Diu	0.0038	0	0
Manipur	0.3367	0.03	103.7	Pondicherry	0.0475	0	0
Meghalaya	0.265	0.03	69.2	**All India**	**257.12**	**37.34**	**72.7**

Table 2: State wise utilization of percentage of production and storage capacity.

(Source: Directorate of economic & statistics and FCI website)

India is an agriculture-based economy. Infrastructure availability is a major lacuna of our country. The number of farmers having small and marginal holdings was 67% and 18% respectively, whereas large farmers were only 1%. The major food grain produced in India is Rice and wheat. The total food grain production of India was [8] increased from 259.28 MT in 2011-12 to 265.04 MT in 2013-14. The oilseed production (Bhavan 2012) also increased from 29.79 MT in 2011-12 to 32.74 MT in 2013-14. The total agriculture storage capacity of India was 108.75 MT in 2012 and it increased to 117.52 MT in 2014. Hence there is a large-scale gap between the agricultural production scenario and storage capacity of India. To mitigate this gap there is a necessity to analyze strengths, weaknesses, opportunities, and threats in the agriculture storage system of India.

Storage potential for crops in India

In India, about 60-70% of food grains produced remains in the rural sector for varying period. Farmers store grain in bulk, using different types of storage structures made from locally available materials. Storage losses constitute a major share of food grain loss in post-production operations. The grains are stored at Producer's Level, Trader's Level, and Urban Organizational Storage Level. (Acharya 2009) The method followed for storing the grains are - (i) storage in bags and (ii) loose storage. Storage in bags is convenient for short term storage, where grain is intended for very early (Sayyad 2016) onward movement.

Results and Discussions

Interview and Field study

Interviews were conducted with marginal farmers to get deeper insights into the post-harvesting process. A semi-structured questionnaire was used to collect the data from the farmers. Through the interview, we came to know that storage facilities in rural areas are either totally absent or grossly inadequate. Under such conditions, the farmers are compelled to sell their produce immediately after the harvest at the prevailing market prices which are bound to be below. Such distress sale deprives the farmers of their legitimate income. Most of the farmer's education level is below High school, but they are good with farming skills. Landholding per farmer is reducing due to the increase in the number of family members which becomes difficult for farmers to build extra space for storage. Farmers have to keep their Produce in an open area where it is subject to risk.

Brainstorming with farmers

The study aims to gather information from farmers about their crops, farming practices, and any issues they may be facing. To do this, a brainstorming session was organized and 12 farmers were invited to participate. The farmers were divided into three groups, each with four farmers, and were provided with initial guidelines for the session. During the brainstorming session, farmers were asked about different types of crops they grew and the timing of planting and harvest, the size of their farm and the production of different crops, any problems they faced with post-harvesting for different crops, and their main reasons or opinions on these topics. To help organize the information and make it easy to understand, a table was created on a whiteboard in the local language of the farmers as show in image below. The table was used to classify the different categories of answers and helped to systematically arrange the information about the actual problems. This allowed the researchers to easily identify the relation between the problem and the root cause, which is essential for finding solutions. The use of a table on a whiteboard in the local language made it easy for the farmers to understand and participate in the session. This approach helped in understanding the farmers' needs and opinions on the crops and farming practices.

Figure 3

Figure 4

Figure 3-4: Brainstorming session with marginal farmers at village in MP India (Source: Author)

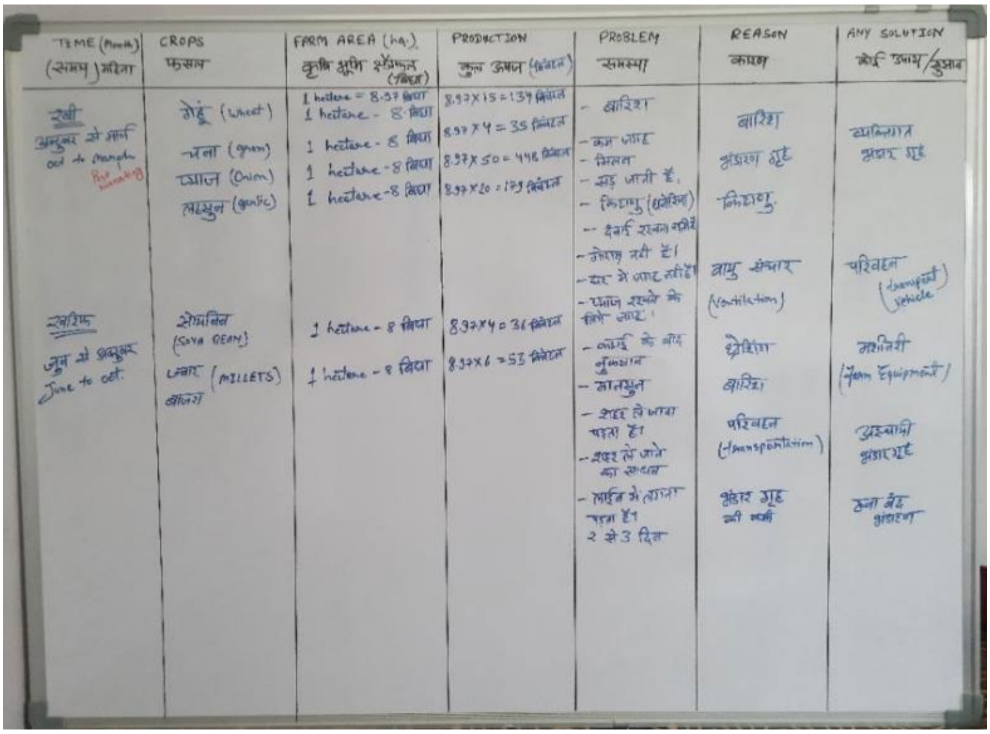


Figure 5: Data collected during Brainstorming and Interview session with farmers (Source: Author)

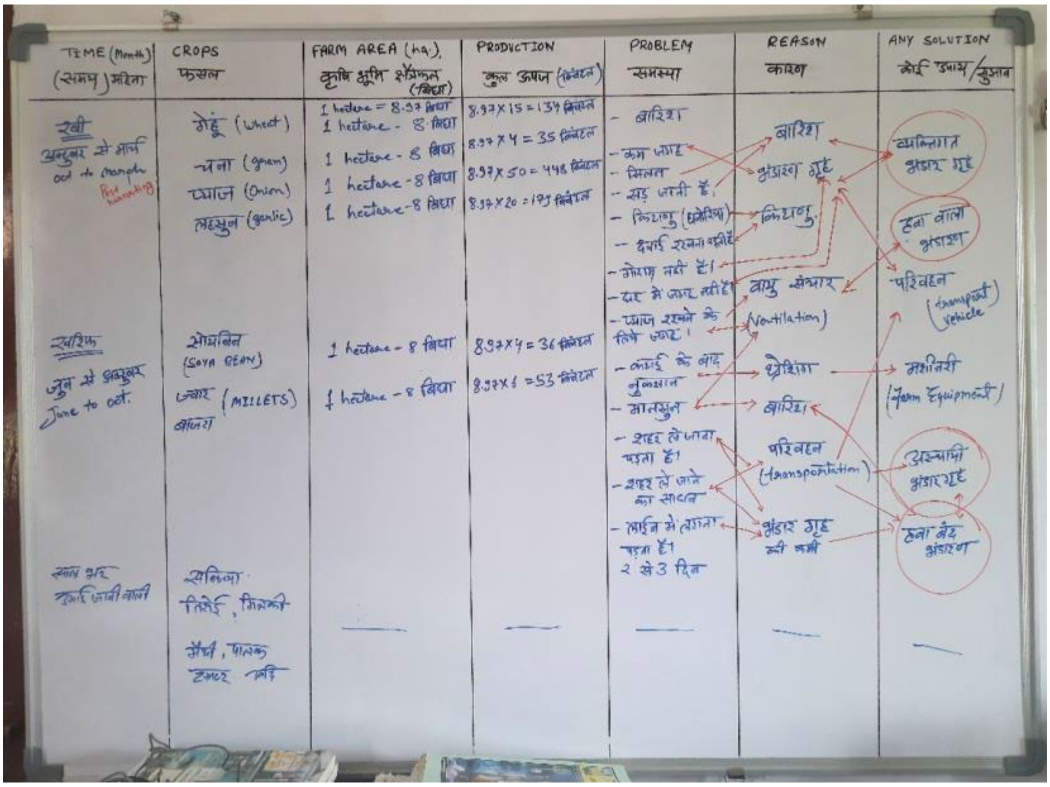


Figure 6: Relation between different problems and root cause according to farmers. (Source: Author)

Insights from brainstorming and Interview with Marginal Farmers

- Marginal farmers often experience significant difficulties in post-harvest management, leading to substantial losses in production.
- One major issue is the lack of storage facilities following threshing and harvesting, which often results in farmers being forced to store their main produce in open fields at their own risk. This vulnerability to climate conditions and monsoons exacerbates the problem.
- Many farmers are reliant on both private and government repositories, yet these facilities are often inadequate, with most godowns unable to store the entire harvest.
- The financial constraints of marginal farmers often prevent them from investing in their own storage space. As a result, farmers are often compelled to sell their produce immediately after the harvest, at prices that are typically low.
- There are no repositories in villages. The absence of repositories in villages further exacerbates the problem, as farmers are then required to rely on transportation such as tractors, trolleys, or trucks, which they cannot afford to purchase or hire.

Participatory design with farmers

The objective of the participatory research with marginal farmers is to gather first-hand information about the storage challenges that farmers face, and to involve them in the process of finding solutions. The research involves a brainstorming session where farmers are asked to share their experiences and insights, followed by a hands-on activity where farmers are given materials like paper, cardboard, tape, glue, etc. and asked to create models of storage solutions based on their own needs and understanding of the problem. This approach allows farmers to be actively involved in the research process, and to provide valuable insights that may not be obtained through more traditional research methods. This approach allows for a more holistic understanding of the issues facing these farmers and can lead to more effective and sustainable solutions.

Figure 7

Figure 8

Figure 7-8: Material and tools for participatory session (Source: Author)

Group 1 - Participatory session with Marginal Farmers for Wheat and Gram Storage

Group 1 was mainly focused on wheat and gram storage after harvesting. They were given a set of required materials and asked to solve the current problem. The main problem was to store the main produce after harvesting as they have less space for the storage.The problem that Group 1 is trying to address is related to the storage of rabi crops typically harvested after April. The main issue is that these crops are sensitive to humidity and moisture and require airtight storage to protect them from damage. However, many marginal farmers lack the space for proper storage, so they are forced to sell their crops immediately after harvesting, which leads to significant losses if the weather is not favorable.

Figure 9: Crops are packed in bags and kept outside *Figure 10: Trolleys are used for storage. (Source: Author)*

After the brainstorming session, we got many insights about the actual problems with wheat and Gram storage. Group 1 was asked to develop a mockup model of their proposed solution,, as shown in fig.11 and 12 below. The researcher also helped with model-making techniques. They came up with a unique solution for storage, which is portable, airtight storage, which is like a traditional trolley used by Indian farmers. Participatory research helped in understanding the farmer's perspective about the problem and bringing their imagination and idea about the solution in a physical form which can be refined further. This approach highlights the importance of understanding the perspective of the end-users and incorporating their ideas in the design process, where low-fidelity prototyping allows users to articulate their thoughts.

Figure 11

Figure 12

Figure 11-12 Farmer from the group -1 suggesting a concept and discussing about the solution. (Source: Author)

Figure 13

Figure 14

Figure 13-14: Storage vehicle with airtight box for wheat and gram (Source: Author)

Group 2 *- Participatory Session with marginal farmers for Wheat and Gram storage.*

Group 2 was also focused on wheat and gram storage after harvesting, as these are two major crops in the Madhya Pradesh area. They were given a set of required materials and asked to solve the current problem. The main problem was storing the main produce after harvesting, as they had less space for storage.

Figure 15

Figure 16

Figure 15-16 Crops are kept in metal drums with the pest killers. (Source: Author)

Similarly, like group 1, farmers in group 2 worked on their proposed solution or suggestion. This group was more focused on individual storage at their farm. They came up with a unique, traditional solution. They made a conical-shaped silo, as shown in fig.19-22 below. Silos are commonly used in agriculture for bulk storage of grain. It has a conical opening at the top, which is used as an inlet, and an outlet at the bottom to extract the grain. The conical shape of the silo has several advantages, such as not allowing rainwater to accumulate on the surface and providing stability during heavy rain and storms. This silo design could be a great solution for farmers who have limited space and resources, as it is relatively low-cost and easy to build. This solution could be more sustainable than the other storage solutions, as its design is inspired by the traditional way of storing grains.

Figure 17

Figure 18

Figure 17-18: Farmer from the group-2 making prototype using paper and thermocol. (Source: Author)

Figure 19

Figure 20

Figure 21

Figure 22

Figure 19-22: Conical storage drum for wheat and Gram (Source: Author)

Group 3 *- Participatory Session with marginal farmers for Onion and Garlic Storage.*

Group 3 was focused on onion and garlic storage after harvesting. These also come in Rabi crops and are harvested with wheat and gram after April. These crops are very sensitive to moisture and monsoons, as they need special storage. We cannot keep mature crops in the field for too long.

The farmers in Group 3 came up with an innovative storage solution that utilizes an open-air shelf structure. They used scrap materials to make a mock-up model of their proposed solution. The design of the storage is specifically tailored to the needs of onion and garlic storage, which require proper inspection and airflow. The structure is made of a metal net, which allows for good ventilation and temperature regulation. The structure has three shelves, which provide ample space for storing the onions. They also suggested to provide a small fan to ensure proper airflow throughout the whole rack. This concept is not only innovative but also very useful for farmers as it allows them to store onions for a longer period of time, up to 6-9 months. The open-air shelf structure allows for proper inspection and airflow, which is important for maintaining the proper temperature and humidity levels necessary for onion and garlic storage.

Figure 23

Figure 24

Figure 23-24: Farmers from group-3 making prototype model with scrap material (Source: Author)

Figure 25

Figure 26

Figure 25-26: Shelf for onion and garlic storage with multiple rack for ventilation (Source: Author)

Designing final solution

Using a prototype, the farmers could communicate their needs and desires with the designer and researcher, which helped the designer gain a deeper understanding of the farmers' perspectives, experiences, and needs. Based on the insights gained from the participatory design process, we as designers, then designed multiple solutions. Out of those, the best suitable one was chosen for modelling and manufacturing. This ensures that the final solution is tailored to the specific needs and desires of the farmers, and is more likely to be accepted and used by them. As show below in figure-27 the final concept is a mobile trolley cum trailor house. This could be used as storage space as well as trailer house at farm. It has Solar panel for basic electricity need at night, ladder,and toolbox for storing essential farm tools.

Figure 27: Final concept model for post-harvest storage (Source: Author)

Figure 28: Rear view (Source: Author)

Figure 30: Side view (Source: Author)

Conclusion

The study attempted to identify the storage problems at the farmers' level and enumerate the losses occurring during storage for the different crops. The problem of post-harvest losses was also captured through a literature review, field surveys, and interviews. By involving farmers in the research, the study was able to gain a deeper understanding of the storage problems faced by farmers. Prototypes made during participatory sessions were used to design a final solution that is tailored to the specific needs and desires of the farmers. Using prototypes, the farmers were able to communicate their needs and desires with the designer and researcher, which helped the designer gain a deeper understanding of the farmers' perspectives, experiences, and needs. Based on the insights gained from the participatory design process, multiple solutions were designed, and out of those, the best suitable one was chosen for modelling and manufacturing. The final concept was designed as a mobile trolley-cum-trailer house that can be used as storage space and a trailer house at the farm. It has a solar panel for basic electricity needs at night, a ladder, and a toolbox for storing essential farm tools. This design ensures that the final solution is more likely to be accepted and used by farmers as it addresses their specific needs and desires. The use of a prototype in participatory design is an essential step in the design process as it helps to bridge the gap between the designer, researcher and users. It helps to ensure that the final product is relevant and valuable to the users and is more likely to be accepted and adopted by them.

References

Acharya S. S. And Agarwal N. L. (2009) Agricultural Marketing in India, Fourth edition Oxford & IBH publishing co. Pvt. Ltd. New Delhi.

Boyce, C., & Neale, P. (2006). Conducting in-depth interviews: A guide for designing and conducting in-depth interviews for evaluation input (Vol. 2). Watertown, MA: Pathfinder international.

Bhavan, K. (2012). Department of Agriculture & Cooperation. Ministry of Agriculture. Government of India.

Council, B. D. (2016). Eleven lessons. A study of the design process. British Design Council.

H. Basavaraja, S.B. Mahajanashetti and Naveen C. Udagatti (2007) Economic Analysis of Post-harvest Losses in Food Grains in India: A Case Study of Karnataka Agricultural Economics Research Review Vol. 20 January-June 2007 pp 117-12

Kishore, A., Pal, B. D., Joshi, K., & Aggarwal, P. K. (2018). Unfolding government policies towards the development of climate smart agriculture in India. Agricultural Economics Research Review, 31(conf), 123-137.

Krishna Kumar, K., Rupa Kumar, K., Ashrit, R. G., Deshpande, N. R., & Hansen, J. W. (2004). Climate impacts on Indian agriculture. International Journal of Climatology: A Journal of the Royal Meteorological Society, 24(11), 1375-1393.

NABARD, P. (2008). National Bank for Agriculture and Rural Development. Mumbai.(2008-2018).

Parwez, S. (2014). Food supply chain management in Indian Agriculture: Issues, opportunities and further research. African Journal of Business Management, 8(14), 572.

Shweta Saini Marta Kozicka (2014) Working Paper 283 Evolution and Critique of Buffer Stocking Policy of India Indian Council For Research On International Economic Relations (ICRIER) India Habitat Centre, New Delhi

Somashekhar, I. C., Raju, J. K., & Patil, H. (2014). Agriculture supply chain management: a scenario in India. Research Journal of social science and management, 4(07), 89-99.

Sayyad, Mr Moin U., and Pramod H. Patil. "STORAGE POTENTIAL FOR AGRICULTURAL COMMODITIES IN INDIA."

Sanders, E. B. N., & Stappers, P. J. (2012). Convivial toolbox: Generative research for the front end of design. Bis.

Sutton, R. I., & Hargadon, A. (1996). Brainstorming groups in context: Effectiveness in a product design firm. Administrative science quarterly, 685-718.

Tara Negi and Dhriti Solanki (2015) Tradition Grain Storage Structures and Practices Followed by Farm Families of Kumaon Region in Uttarakhand Department of HECM, MPUAT, Udaipur Rajasthan

Teegavarapu, S., Summers, J. D., & Mocko, G. M. (2008, January). Case study method for design research: A justification. In International design engineering technical conferences and computers and information in engineering conference (Vol. 43284, pp. 495-503).

Agnivesh Sharma

Agnivesh Sharma is a Ph.D. scholar at IDC, IIT Bombay, working on the development of an adoption model for sustainable farming in India. As a certified permaculture designer, he employs his expertise to support farmers in designing eco-friendly farmland using ecological principles. Agnivesh's research focuses on participatory design, collaborating directly with end-users to uncover their implicit needs and desires. Prior to his academic pursuits, he worked as a Human Factor and Industrial Design Engineer at the renowned medical equipment manufacturer, Boston Scientific. Agnivesh's passion for sustainable farming and user-centric design has driven his commitment to making a positive impact on the agricultural sector in India.

Nishant Sharma

Nishant Sharma is a Professor of Mobility & Vehicle Design at IDC School of Design, IIT Bombay. With a strong focus on Vehicle Form & Aesthetics, Mobility Design, and Participatory Design, he has played a pioneering role in shaping India's first specialized Transportation & Automobile Design program at the National Institute of Design, Ahmedabad, and establishing the Mobility and Vehicle Design program at IIT Bombay. As an educator and researcher, he teaches postgraduate courses, supervises Master of Design and PhD students, and leads funded research and consultancy projects with government, private companies, and non-governmental organizations. His expertise in Bionics, Human-Powered Mobility, and Nature & Form has cemented his position as a leading figure in mobility and vehicle design in India.

A virtual reality experiential prototyping tool for the application of anthropometry in complex, confined human environments.

Peter Schumacher, University of South Australia
Francois Fraysse, University of South Australia
Brandon Matthews, University of South Australia
Simon Modra, University of South Australia
Ross Smith, University of South Australia
Dominic Thewlis, University of Adelaide
Geoff Langridge, Kadego Cadgile
Jack Beven, Kadego Cadgile

Abstract

Designing complex confined human environments requires the rigorous application of anthropometry to ensure that the environments are fit for use for the full range of body sizes in the target population. While anthropometry is a well-established discipline, the tools and methods for its application are not as developed and refined. Important tools for applying anthropometry are physical models and Digital Human Manikins (DHMs), used in CAD and ergonomics software. DHMs currently need to be posed body segment by body segment, which is cumbersome, time-consuming and requires an expert user. Also, they do not provide designers with direct experiences of different body sizes in environments. The challenges associated with the development and use of DHMs reduces their impact and effectiveness as part of the design process. The Real Anthropometric Experience System (RAES) presented in this paper addresses the current limitations by providing a new way of engaging in prototyping with DHMs that gives designers experience using different body sizes, leading to a more empathic understanding of the environment for different users. The system has two tools, a DHM poser and a Virtual Reality (VR) environment. In the first tool, the user moves in front of a motion capture device while viewing a screen showing a DHM that is driven by their body movement in a virtual environment. Users can pose DHMs with different body sizes and experience the different postures required to achieve a goal. Poses are captured and exported to CAD. In the second tool, the designer enters a VR environment from the viewpoint of a DHM, their body is tracked and the DHM moves with them in real time. They can 'inhabit' different body sizes to gain a physical and visual sensation of being in a different body that would otherwise be impossible to achieve.

Anthropometry; Virtual Reality; Ergonomics; Digital Human Manikins; Human Centred Design

This paper describes new prototyping methods and tools developed for the application of anthropometry in the design of complex, confined human environments. It describes the Human Centred Design (HCD) methods developed in the Studio for Complex Human Environment Design (SCHED) for the design and assurance of habitable spaces in isolated confined environments (ICEs). This paper critically evaluates the limitations associated with the current prototyping tools and methods that make applying anthropometry challenging and lacking in experiential richness. New design methods and tools using body motion tracking and virtual environments were developed, enabling designers to interact with and evaluate virtual prototypes more effectively and understand the physical experiences of different body sizes in environments.

Anthropometry and Design for ICEs

When designing a product, clothing, or environment it is important that the item is sized to suit the range of body sizes in the user population. Anthropometry is a science that describes the physical measurements of people's bodies in a specified population, it is used in the design and assurance of products and environments (Pheasant & Steenbekkers, 2005).

The application of anthropometry is particularly important and challenging when designing for high-risk, high-stakes, confined environments such as aircraft cockpits, cars, trains, mining, emergency medical facilities, and habitation such as oil rigs, submarines, and off-world accommodation (Mallam et al. 2015, Harrison & Connors, 1990). The allocation of space in these extremely confined habitable environments requires careful design to balance the spatial needs of the users with space required for the various technical systems. Poor sizing and layouts of these environments negatively impact people's ability to work effectively and live comfortably. For example, a survey of US Navy personnel found that unsatisfactory living conditions such as limited room in the cabin areas and berths as well as poor showers and head spaces had a negative effect on performance and crew retention (Wilcove & Schwerin, 2008).

In 2015 the Royal Australian Navy conducted an anthropometry survey of their personnel to aid the procurement, development, and assurance of naval platforms resulting in the Anthropometry Survey for the Royal Australian Navy (ASRAN) (Ponton et al., 2019). The prototyping tools and methods described here were part of a larger project to develop a HCD method to improve habitability onboard submarines. The DHMs in this paper are based on the ASRAN data, using a Boundary Manikin approach that uses statistical methods to identify individuals at the edges of the target population (Young et al. 2008). We selected these to ensure the design would accommodate the diverse range of different body shapes and sizes within the target audience.

While the gathering and analysis of anthropometric data is a well-established discipline, the tools, and methods for the application of anthropometry are not as developed (Dianet et al., 2018). A given environment will typically need to accommodate a wide range of use scenarios. The design methods and tools therefore need to be efficient and easy to use so that designers can investigate, understand, and propose designs to address all the scenarios within the constraints of the project time and budget.

Requirements for a specific environment can specify explicit accommodation levels, e.g., "95% of the users should be able to perform task X successfully". This is usually assessed by identifying the individuals at the extremes of the target population, and assessing whether these individuals can successfully complete the task. *The extremes* are often in practice extremes of body size.

The HCD approach requires an understanding of the users' tasks and environments that is obtained by engaging with users are involved throughout the design process (ISO, 2010).

Users provide information about the context of use, use scenarios and how people engage with systems and environments. In addition, users are involved in the design providing feedback, evaluation, and input throughout the process. It is important to understand the user's activities for the interpretation and application of anthropometry.

Prototyping

Prototyping occurs at all stages of the design process as part of the transition from vagueness to clarity and has been described as shorthand for design (Kelly, 2001). Prototypes represent ideas and give form to abstract concepts and are used to supplement incomplete mental models (Camburn et al., 2017). Mock-ups create 'hands-on-experiences' and their unfinished nature distinguishes them from the actual environment aiding people understand that the prototypes are tools in communication and idea generation (Vaajakallio & Mattelmäki, 2007). There are many types of prototypes for example, written descriptions, images, computer algorithms, computer models and various types of physical modelling. The types of models, the level of detail, visual characteristics and degree of functionality change over the course of the design process.

Models made early in the process have a key role in helping the designer and client understand the problem and redefine the requirements (Andriole, 1994). Simple models generally open up the solution space and suggest more opportunities and options, hence they are used earlier in the process, whereas more detailed models narrow the solution space and are used later in the process (Vaajakallio & Mattelmäki, 2007). It is part of the designer's craft to decide on the appropriate level of abstraction for the stage of the design and the nature of the issues being addressed (Säde, 2001).

Existing Prototyping Tools and Methods for Applying Anthropometry

There are two main prototyping approaches for applying anthropometry as part of the design process, digital modelling and simulation and physical modelling.

shows the different types of prototyping (digital and physical) used throughout the design process for the application of anthropometry. The table uses the Double Diamond design process (Design Council, 2018) used by SCHED.

In general, existing tools for applying anthropometry are challenging to deploy making it difficult to integrate them early and often in the design process. The RAES, described later in this paper, was developed to make it easier to apply DHMs throughout the design process.

Table 1 – Methods for applying anthropometry as part of the HCD process for ICEs.

	Activities	Digital Prototyping-DHMs	Physical Prototyping
Discover	The problem exploration stage of the process is concerned with collecting information about the users, their needs, and the context. The population is defined and the range of sizes to be addressed is decided.	CAD and VR models are made to explore and establish the technical and ergonomic constraints. The anthropometric data is analysed and DHMs are developed and sized to suit the chosen population.	Simple physical models are used to reflect the sizing of the environment and major components. These aid the design team visualize and understand the problem and are used to engage with users to help them describe their needs and problems.
Define	Findings from the Discovery stage are distilled to provide constraints around size and reach envelopes, task performance and operational efficiency. User needs are described as scenarios and criteria that inform the interpretation and application of the anthropometry and the posing of DHMss.	CAD models are used to describe the specifications and constraints such as reach envelopes, body sizes and poses based on the use scenarios. Anthropometry data bases are used to define spatial constraints. DHMs are posed based on the use scenarios identified in the Discover stage.	Physical prototypes defining key dimensions for human fit are built to support the Develop stage activities.
Develop	Designs are developed as physical, CAD and VR models and evaluated by users as part of an iterative design process. Users are consulted and DHMs are used to ensure the design suits the full range of sizes in the population.	CAD models of increasing fidelity are developed as part of an iterative process of development. The CAD models are built around the DHMs that were posed in the previous Define stage. This ensures the human sizing is present throughout the Develop stage. Based on the CAD models VR experiences are developed. These include various sized DHMs so that the designers can experience the spaces in context with the range of user's body sizes.	Physical models of increasing fidelity are developed as part of an iterative process of development. Stakeholders and people selected based on having body sizes at the population extremes interact with the prototypes to give feedback on the sizing.
Deliver	The design is described in terms of user needs and body sizes.	CAD models are created that define the spatial arrangement of the design. DHMs are used in the documentation to describe how the design accommodates the various body sizes. Documentation includes VR experiences, flythroughs, static images, and reports.	High-fidelity physical mock-ups are made for stakeholder engagement and final assurance activities.

Digital Prototyping

On the digital side DHMs are software representations of humans used to visualize human bodies in relation to a design. DHMs can be made to reflect any body size from a specified population database in a virtual environment. Specialist DHM software including Jack^{TM}, Ramsis^{TM}, and Safework^{TM} and are typically used in parallel with Computer-Aided Design (CAD) programs. CAD models are imported into the ergonomics software where the DHMs are used to evaluate the designs. Alternatively, DHMs as stand-alone CAD models can be placed into CAD environments to guide the design development and for analysis. Crowded environments like control rooms and public transport can be populated with multiple DHMs.

Digital assessments with DHMs have the advantage of lower cost (once the software and computer hardware has been amortised) compared to physical models, and the potential to be used earlier in the design process. They also allow simulating a population of any size. However, they provide a much lesser degree of certainty in the assessment; in our experience, DHMs are never used as the final check for design validation. This is due, in large part, to the fact that operating DHM software is done almost entirely manually by the user, including posing DHMs and generating motion. Motion simulation is a highly complex problem; as such, DHM software currently only provide very basic automated posing tools.

Physical Prototyping

Physical prototyping techniques are used by designers to ensure a good fit between the environment and the range of body sizes in the nominated user population. Physical prototyping is often more time and resource-consuming than digital models. However, it provides the most direct experience of the environment; it allows experiencing factors that digital assessment doesn't (e.g. touch, sound, lighting), allows problem detection (e.g. collisions, awkward postures) at a finer and more realistic level than DHMs, and non-expert users can navigate and experience the space freely. The level of confidence for design assessment through prototypes is much higher than digital.

For example, the full sized DHM cut outs in Figure 1 show the extreme body sizes that needed to be accommodated for a project. Note, the tallest and shortest members of the design team (shown on the left) did not reflect the extremes of the population. Any evaluation of a physical prototype by a designer with their own bodies is problematic and care must be exercised to ensure that the designers' personal experiences are not used as a proxy for users of all sizes.

A designer developing a kitchen will experience the bench height, sight lines and storage access based on their body size. Consulting anthropometric data for relevant body dimensions, looking at DHMs in virtual models, and observing and interviewing users at the extreme body sizes will aid the designer, but the designer will lack the direct experience of other body sizes and must remain conscious that their physical experience cannot be relied on for decision making.

Figure 1 - Designers (on the left) and people selected for extreme body sizes (on the right), compared to the extreme body sizes from the ASRAN data.

One way to address this problem is to identify people that are very close to the extreme body sizes that need to be accommodated and ask them to participate in design evaluation exercises. The people on the right in Figure 1 are an example of people selected because they are close to the extreme body sizes to be accommodated. Figure 1 shows them evaluating the ability to reach controls from a seated position. However. recruiting individuals of extreme body sizes, in sufficient numbers to have sufficient statistical power, can be difficult.

It is important to note that people have a range of body sizes, shapes, and proportions. For example, a group of people with the same stature will have a range of leg length to torso proportions. Therefore, selecting people for the extremes of the population requires careful consideration and compromise. People are typically identified based on stature and weight but for some tasks, such as seated activities, the leg-to-torso proportion may be important, further complicating the task of using people to evaluate physical prototypes.

Figure 2 - People chosen to evaluate a design based on their extreme body size.

Developing New Tools and Methods - RAES

The RAES is SHED's response to alleviate the shortcomings of current DHM tools. The project was developed by a team that included VR software researchers, biomechanics researchers with expertise in anthropometry, industrial designers, architects with experience in applying anthropometry in the design of ICEs, and industry partners with experience in CAD, VR, and environment design.

The new tool is called the Real Anthropometry Experience System (RAES) and was developed based on the following assumptions.

1. The maturing of gaming software (the Unity™ engine), motion tracking (Kinect™) and VR technology (Oculus™ headsets) provided an accessible and cost-effective platform to:
    a. Develop immersive environments.
    b. Enable VR experiences.
    c. Track people's body movements in real time and match these to digital manikins.
2. Posing manikins would be based on tracking people's body motions, eliminating the need for the complex, artificial, screen-based interface currently used to pose DHMs.
3. People's poses (based on their own body sizes) can be translated to different virtual body sizes and proportions.
4. Users can able to adjust their perception and movement to suit virtual bodies that have different sizes and shapes.
5. Users inhabit a VR environment with different body sizes enabling designers to understand the implications of the design for sight lines, reach and movement for a

range of body sizes.

The tool needed to be easy and efficient to use, require minimal training (assuming the tool is used by a team with some CAD skills) and integrate with the other prototypes and design assets being developed in parallel.

The RAES tool has two elements: a DHM pose capture tool, and an immersive VR experience.

RAES DHM Pose Capture Tool

To use the RAES DHM Poser Capture Tool the designer moves in front of a motion capture device while viewing a screen that shows their body moving a DHM in real time in a virtual environment. They can change to different DHMs to see and experience the postures required by different body sizes to achieve the same goal. The DHM poses can be captured and exported to CAD software for use in virtual prototyping. This makes it faster and easier to make DHM poses that are realistic compared to existing DHM posing systems. By making posing easier DHMs are more likely to be used early in the design process.

Figure 1 shows the set-up, a laptop, and a body motion sensing device, in this case a Microsoft Kinect™. Figure 2 shows the pose of the designer and what the designer sees on the computer screen.

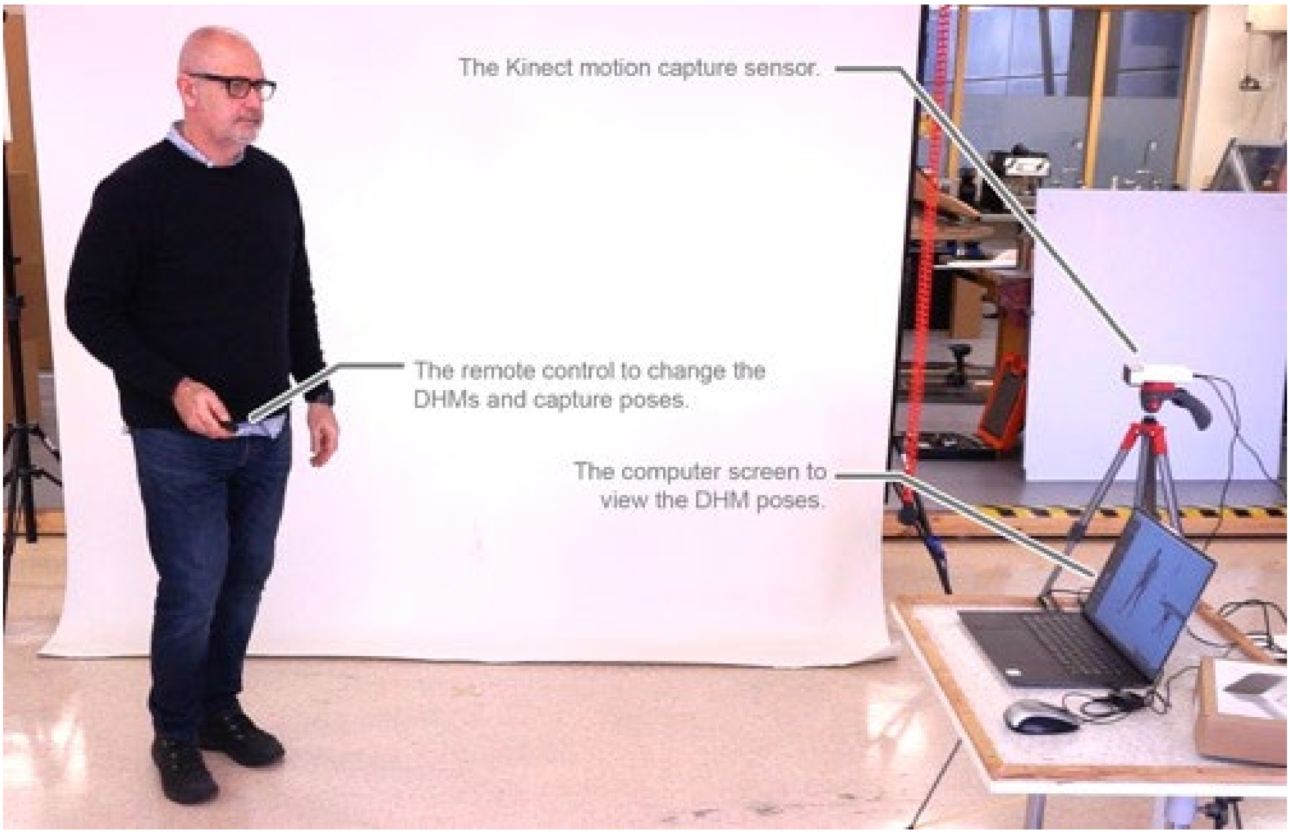


Figure 1 - The RAES poser hardware set up.

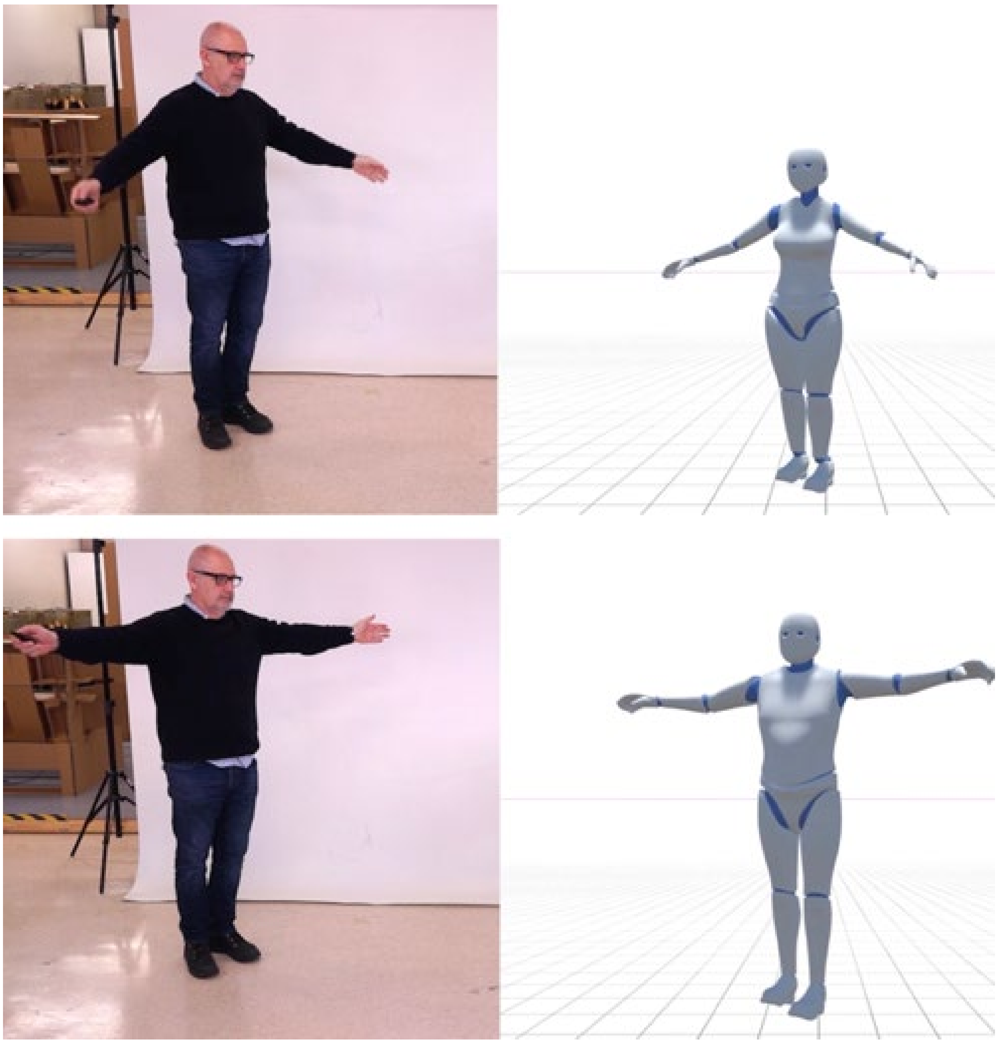


Figure 2 - A designer’s pose being reproduced by a small female DHM (top row) and a large male DHM (bottom row).

A key feature is the ability to import a CAD model so that the DHMs can be posed in context. Figure 3 shows DHMs being posed in an ambulance environment. For this design it was important that the users have good access to controls located on the ceiling. The pose on the left shows the designer reaching the ceiling device as the large male DHM. The pose on the right shows the designer reaching for the same point as the small female DHM: note the more extreme stretch required. This provides the designer with a direct physical experience of what it feels like to be different body sizes in the environment.

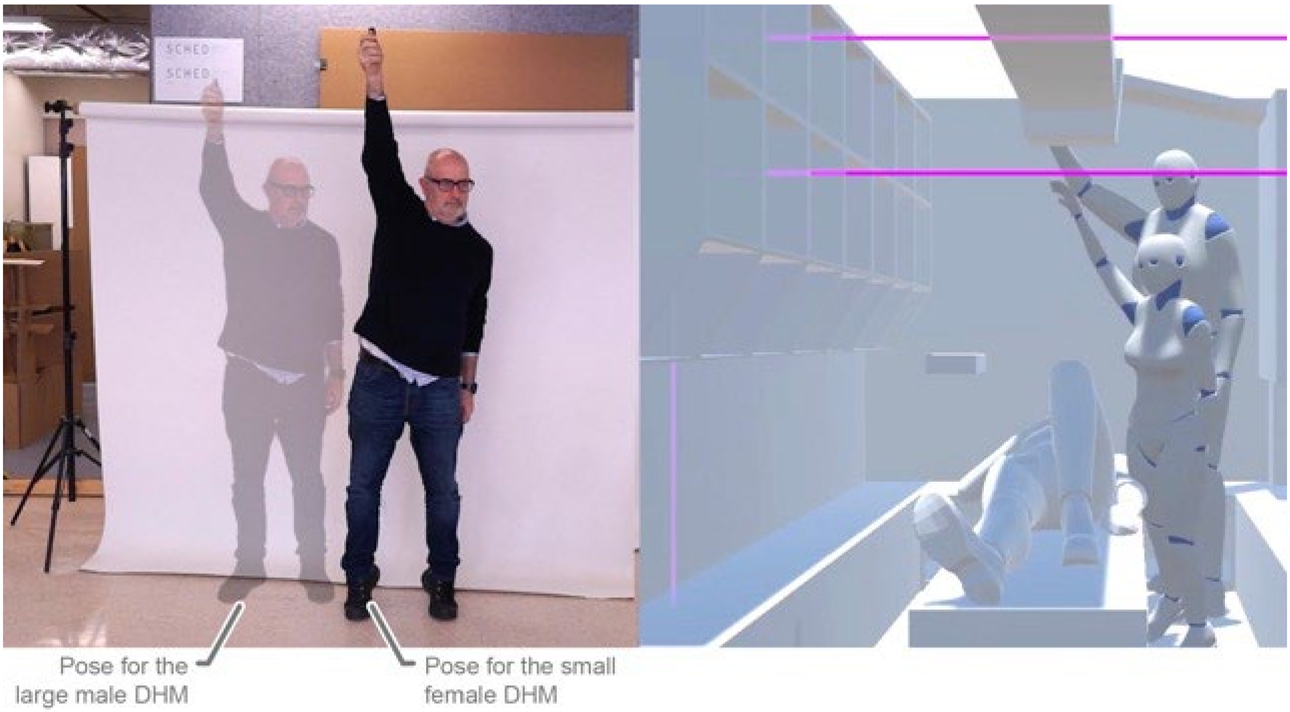


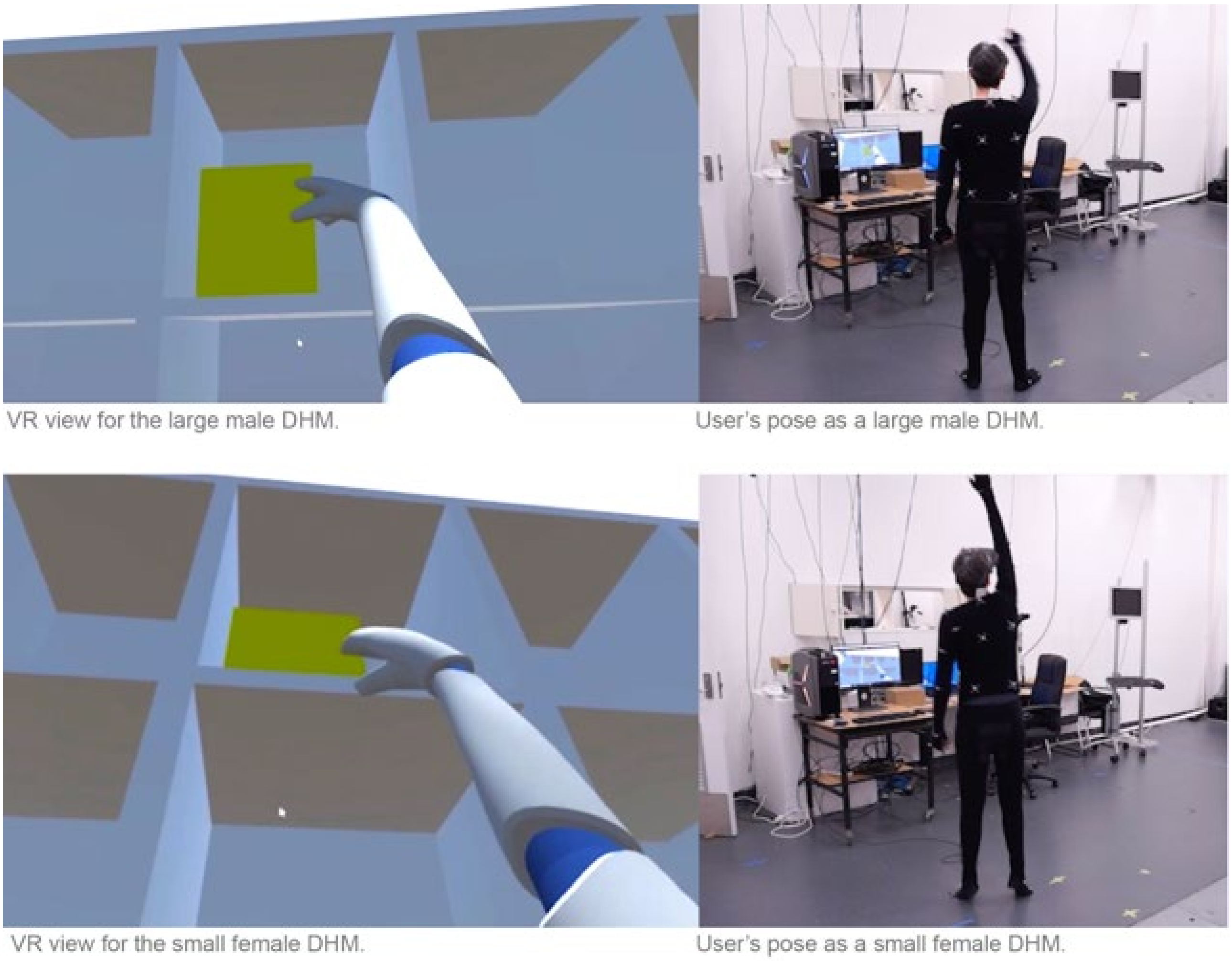
Figure 3 - Postures the designer takes when using RAES to reach the same target as different body sizes.

RAES Immersive VR Experience

The designer enters a virtual environment inhabiting a DHM, as they move the DHM moves with them in real time. They can select different body sizes enabling them to evaluate the reach and sightlines of people with a wide range of statures and body segment proportions. This gives them a direct physical sensation and experience that would otherwise be impossible to achieve. The movement through the virtual space is accomplished by a real human, removing the issue of digital motion simulation.

The system requires a VR headset, computer, and body motion tracking. The current tool uses the Optitrak™ motion capture system that requires reflective markers located on the body and expertise to set up. The existing system is cumbersome and goes against the goal of user-friendly integration, however, it is anticipated advances in marker-less motion capture will alleviate the issue soon.

Figure 4 shows the RAES VR tool being used, with the user inhabiting a large male (the top row) and a small female (the bottom row) simulating reaching a yellow box on a high shelf. The image on the left shows the point of view from the VR headset. Note the different body postures taken by the designer to reach the box as different body sizes. As the large male the designer takes a lower, easier posture to reach the box, in comparison the small female needs to stretch up much more to access the box. Also note the differences in the sight lines, the small female has a restricted view of the box compared to the large male.



VR view for the large male DHM.

User's pose as a large male DHM.

VR view for the small female DHM.

User's pose as a small female DHM.

Figure 4 - The postures taken by a designer when inhabiting different body sizes to see an object under a bench.

Figure 5 shows the RAES VR tool being used with a large male (the top row) and a small female (the bottom row) DHM moving through a control room. Note how restricted the sightlines are for the small female compared to the large male.

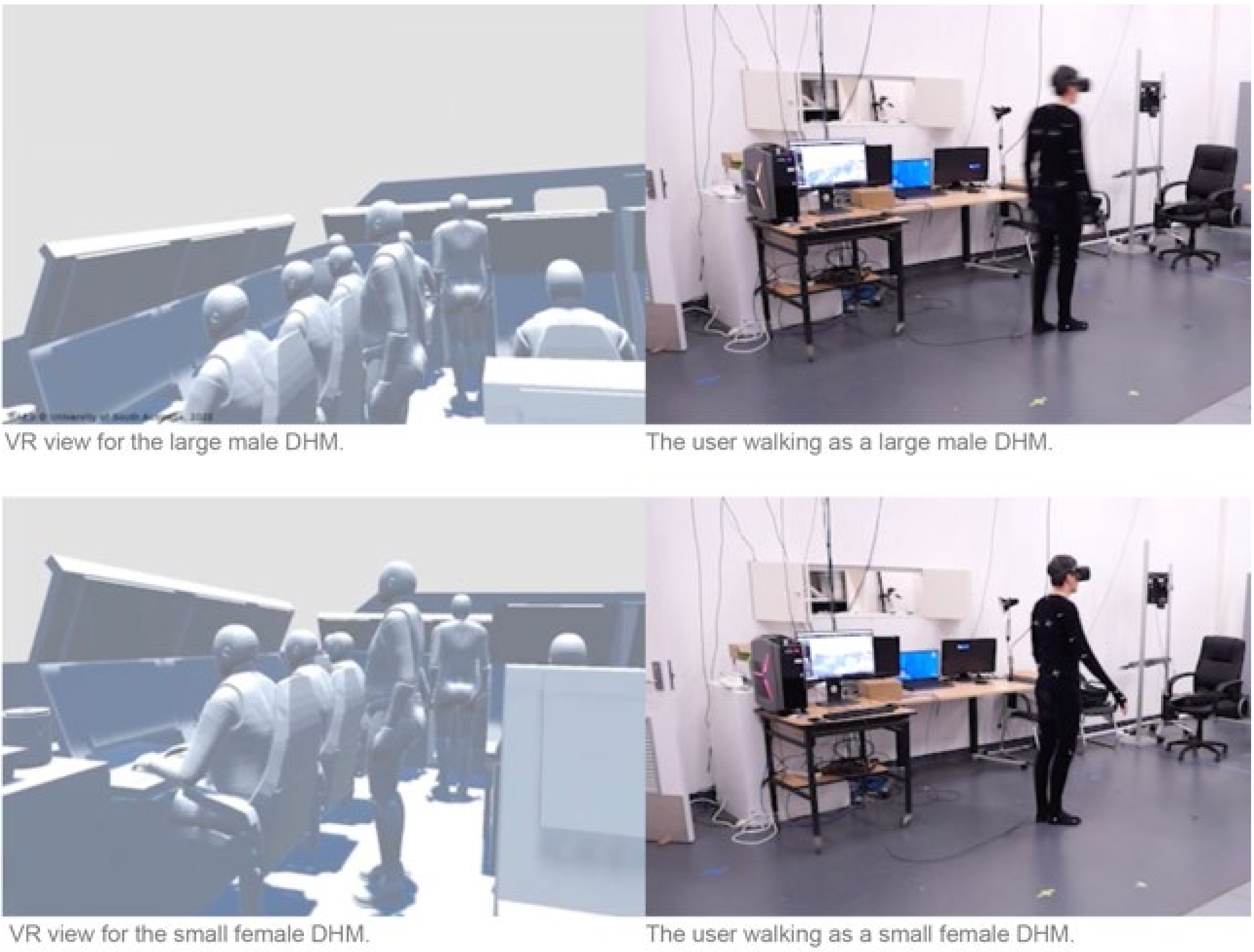


Figure 5 - The point of view seen by a designer when inhabiting different body sizes.

Evaluation of the VR tool

One important condition for the viability of the RAES system is that, when a user is embodying a DHM of a different body size than their own, the user's movement should replicate the motion of a user of this actual body size. If a 1.70m stature male embodies a 1.95m stature DHM, the user's movement in the VR environment should match the movements of an actual 1.95m tall person in the real world.

To test this, we ran the following experimental study at the Wearables Computer Lab of the University of South Australia. 30 participants were recruited from the public. Of those, 10 participants were selected based on their body size: five so-called large males, over 1.90m tall and over 90kg; and five small females, under 1.54m tall and under 50kg. The other 20 participants had no restrictions on anthropometry.

Participants were fitted with the Optitrack™ motion capture suit (a full-body Lycra™ suit) on which retroreflective markers were attached. They were also fitted with the Oculus™ VR headset. They were then asked to perform a set of seated reach tasks under three conditions:

- In the first condition the participant did not wear the VR headset. They were seated at a physical desk upon which a large vertical panel was attached. On the panel were printed 13 radiuses originating at the centre of the intersection line between the desk and the panel (Figure 6). Using their right hand, they were asked to perform maximum reach in the direction of the radius specified by the researcher, maintain the maximum reach position for one second, then return to rest. Each direction was tested twice, and the order of the directions tested was randomized. Reach distance was measured using tick marks spaced by 50mm on each radius.

- In the second and third conditions, the same setup as above was replicated in Virtual Reality. Participants wore the VR headset, seated on a chair, and were presented with a replica of the physical setup above (desk and panel) in the VR environment. Their body size was scaled to that of a ASRAN large male (1.94m tall) or small female (1.54m tall), The maximum reach tasks were repeated.

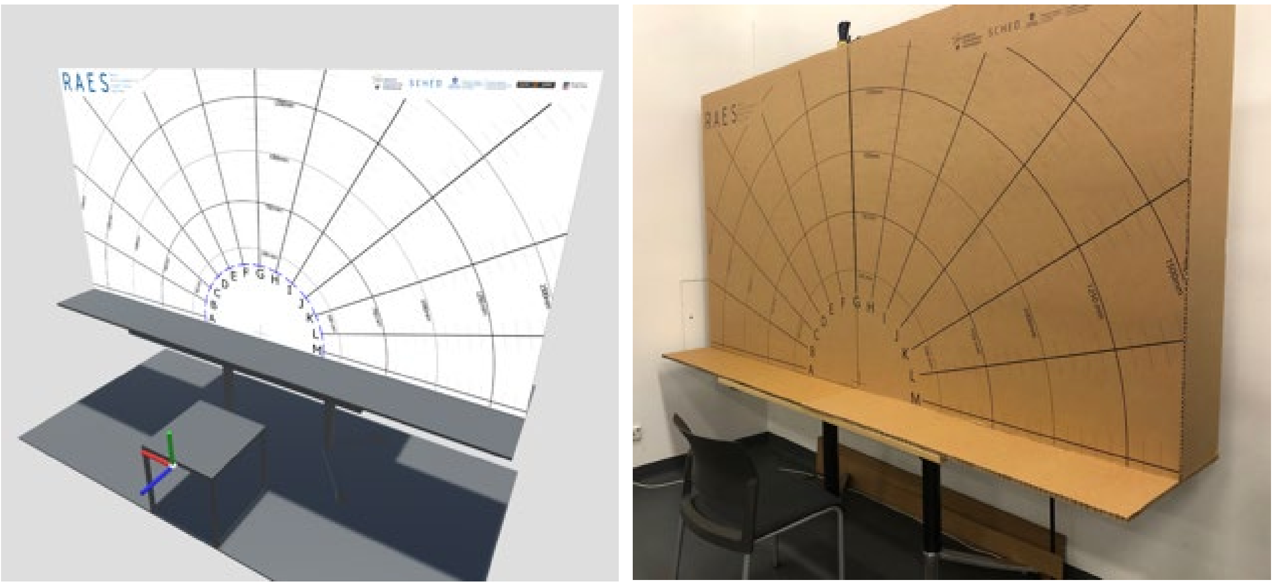


Figure 6 – experimental setup for reach capacity assessment.

Maximum reach distances for each condition were processed for each participant. Initial results (as of 21/03/2023) indicate that, when participants are scaled to large male or small female body size in the VR environment, their reach capacity match that of an actual large male or small female, to within intra-individual variability (analysis is in progress).

Conclusion

Developing designs for human fit in complex confined environments requires the use of a range of prototyping tools and methods. Existing tools and methods provide a limited understanding of the experience of bodies in space and are expensive and difficult to use. Based on extensive experience applying anthropometry for design, new tools and methods were developed, with the aim to provide an experiential and empathic experience for designers the existing methods do not provide. The key element is that the designers would use their bodies to manipulate the DHMs to make the task easier, faster, and create more realistic DHM poses. It also provides the designer with the physical experience of body movements as different body sizes. In this way RAES can be understood as an advanced form of bodystorming. Also making DHM manipulation easier and faster means they are more likely to be used in the early stages of the design process.

The approach hinges on the use of DHM not as a quantitative assessment tool, but rather as a qualitative tool helping designers and engineers get a better feel and understanding of the issues associated with a potential design. We believe that, given the current limitations of motion simulation, DHMs are currently unable to provide enough confidence in design evaluation to be used as a validation tool. However, they do provide benefit in the design process by enabling quantitative assessment and visualization, and by doing so at an earlier stage than physical prototypes. One of the main challenges associated with the use of DHM is making their use better integrated with the overall design process. At present, most DHM tools are part of specialised software packages, which represents an additional burden in the overall process (e.g., obtaining, installing, and learning such software; import and export of CAD models from software). In that sense, RAES also represents an attempt at better integration of DHM tools in the overall design workflow.

References

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., ... & Wood, K. (2017). Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science, 3, e13.

Design Council (2018) The Design Process: What is the Double Diamond? Available at: https://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond [Accessed: 3 Sep 2018]

Dianat, I., Molenbroek, J., & Castellucci, H. I. (2018). A review of the methodology and applications of anthropometry in ergonomics and product design. Ergonomics, 61(12), 1696-1720.

Harrison, A. A., & Connors, M. M. (1990). Human factors in spacecraft design. Journal of spacecraft and rockets, 27(5), 478-481.

ISO DIS 9241--210. Ergonomics of human system interaction - part 210: Human-centred design for interactive systems. Tech. rep., International Organization for Standardization, Switzerland, 2010.

Kelley, T. (2001). Prototyping is the shorthand of innovation. Design Management Journal, 12(3), 35-42.

Lämkull, D., Hanson, L., & Örtengren, R. (2009). A comparative study of digital human modelling simulation results and their outcomes in reality: A case study within manual assembly of automobiles. International Journal of Industrial Ergonomics, 39(2), 428-441.

Mallam, S. C., Lundh, M., & MacKinnon, S. N. (2015). Integrating Human Factors & Ergonomics in large-scale engineering projects: Investigating a practical approach for ship design. International Journal of Industrial Ergonomics, 50, 62-72.

Pheasant, S. T., & Steenbekkers, L. P. A. (2005). Anthropometry and the design of workspaces. In Evaluation of human work (pp. 715-728). Taylor & Francis.

Ponton, K., Huf, S., Gamble, D., Coleman, J., Furnell, A., & Cockshell, S. (2019). Revised Anthropometry Guidance for the Royal Australian Navy.

Säde, S., 2001. Cardboard mock-ups and conversations: Studies on user-centered product design. University of Art and Design Helsinki UIAH.

Vaajakallio, K., & Mattelmäki, T. (2007, August). Collaborative design exploration: envisioning future practices with make tools. In Proceedings of the 2007 conference on Designing pleasurable products and interfaces (pp. 223-238).

Wilcove, G. L., & Schwerin, M. J. (2008). Shipboard habitability in the US Navy. Military Psychology, 20(2), 115-133.

Young, K. S., Margerum, S., Barr, A., Ferrer, M. A., & Rajulu, S. (2008, January). Generation of Boundary Manikin Anthropometry. In 38th International Conference on Environmental Systems (No. 08ICES-0290).

Dr. Peter Schumacher

Dr. Peter Schumacher has a Bachelor of Architectural Studies from Adelaide University and a Bachelor of Industrial Design (first class honours) from the University of South Australia. His PhD from the Australian National University was on the design of pictorial assembly instructions for use in developing countries and on methods of researching and codifying knowledge for human-technology interaction design.

He has led numerous industry collaborations including; a nurse call button for people with arthritis with Hills Industries and Eldercare that received national and international awards, surgical device design, and control room computer consoles for the Future Submarine Technical Organisation and Saab.

He is currently leading a project for the Australian Defence Science and Technology Group to examining design and development methods for submarine habitable spaces. The project deploys user centred investigation and development design methods to improve usability, and the practical application of anthropometry and fatigue research.

Dr. Francois Fraysse

Dr Fraysse is a Senior Research Fellow in the Allied Health and Human Performance Unit of the University of South Australia. He has a background in mechanical engineering and biomechanics.

His current research activities fall in two key areas. First he is involved in biomechanics applied to human performance and human factors. In particular, he is currently involved in multiple projects with the Australian Defence Science and Technology Group, and the Australian Transport Industry, using biomechanical methods to develop digital models of physical performance and space requirements of military personnel.

His second area of activity is the objective measures of use-of-time and physical activity in populations using body-worn activity monitors. He specialises in the development of new signal processing methods allowing precise assessments of individuals' physical activity patterns, using body-worn activity monitors (accelerometers).

These research activities have resulted in over AUD $6M in competitive funding, 44 international publications and has a Scholar h-index of 18.

Simon Modra

Simon Modra is a highly experienced design practitioner who operates a sole practice based in Adelaide. He has extensive knowledge and expertise in interior architecture, furniture design, building design, and project management, holding a Master of Architecture, Master of Design (Design Construct), Bachelor of Architectural Studies, and a Diploma of Business. Simon is also a part-time PhD candidate and design researcher contracted by The University of South Australia as a founding member of the research outfit SCHED (Studio for Complex Human Environment Design).

Simon’s PhD topic “Strategies for integrated use of simulation tools for designing human spaces in Capsule Environments,” focuses on virtual and physical prototyping and understanding the capabilities of models made in virtual reality (VR) versus physical full-scale models in the process of Human Centered Design (HCD).

Brandon Matthews

Brandon Matthews received his Bachelor with Honours of Software Engineering from the University of South Australia in 2016. He is a PhD candidate at the University of South Australia and IVE: the Australian Research Centre for Interactive and Virtual Environments. His research interests include perception and illusions in VR, haptic user interfaces and computer graphics.

Associate Professor Dominic Thewlis

Associate Professor Dominic Thewlis works in the field of biomechanics (the application of mechanics to understand biological phenomena), specifically orthopaedic (our bones, muscles, tendons and ligaments) biomechanics. He was a NHMRC R.D Wright Fellow (2017-2021) and is recognised as an emerging leader in the field with awards from the International Society of Biomechanics (footwear biomechanics group), International Foot and Ankle Biomechanics community, Australian and New Zealand Orthopaedic Research Society, and the ORS (USA). Dominic is the immediate Past-President of the Australian and New Zealand Orthopaedic Research Society, and editorial board member for the Journal of Biomechanics and Gait and Posture.

Associate Professor Ross Smith

Associate Professor Ross Smith is a member of the Australian Research Centre for Interactive and Virtual Environments (IVE) leadership team and is Director of the Wearable Computer Lab at the University of South Australia. His research strengths focus on interactive systems to support health and medical technologies that are informed by industry challenges. He has extensive experience with virtual/augmented/mixed reality, novel interaction devices, deformable surfaces, input device hardware development, and user interface design.

Geoff Langridge

Geoff Langridge has over 25 years' experience in mechanical engineering and CAD, primarily in the manufacturing industry. He has a degree in mechanical engineering and information technology along with a trade background and has designed mechanical products, machines and systems for various industries including automotive, rail, agriculture and defence. His skills include project management, team leading and mentoring as well as advanced IT skills such as API/SDK programming. In addition he is a high level user of NX, Solidworks and Teamcenter and has strong experience with Catia V5/6, Creo and 3DExperience.

Jack Beven

Jack Beven is a software developer with a background in digital art and experience in digital media and modelling.

Track 7: Materials and Digital

- Exploring 3D Printing Strategies for Designers to Reach Circularity
- Adaptive Materials and The Role of Design[ers] (Research[ers]) in Shaping Transformative Futures
- Constructing e-textile prototypes to inspire improvised behaviour
- Feeling Fabrics: Prototyping Sensory Experiences with Textiles and Digital Materials
- Beyond Boundaries: 3D Printing and Functional Materials as Boundary Objects to Mediate Interdisciplinary Collaboration

Exploring 3D Printing Strategies for Designers to Reach Circularity

Patrizia Bolzan, Politecnico di Milano - Department of Design
Lexing Xu, Freelance designer and researcher

Abstract

Additive Manufacturing has been identified as a disruptive emerging technology and has great potential for sustainability and the implementation of the circular economy. However, to date, new generations of designers have tended to utilize it as a mere tool for the three-dimensional representation of a solution conceived and designed for other supply chains. This not only creates experiential and perceptual problems in relation to AM but actually represents a misuse of material resources, which are utilized in an uninformed manner.
With this in mind, the paper aims to chart possible directions and strategies to foster an informed use of AM within the Circular Design design and production process.
After an introductory framing of the current issues and peculiarities of AM, we present the five strategies identified to enhance the potential of 3D printing within the framework of the ecological transition. These strategies are the starting point for defining a roadmap to better understand and consciously use AM in the design of circular and sustainable solutions.

Additive Manufacturing; Study Model; 3D Printing; Circularity; Circular Design

The educational path related to Design as a discipline is composed of the transmission of a variety of knowledge, multidisciplinary and interdisciplinary, for the constitution of a professional skilled in both the conception and communication of solutions responding to the principles of innovation, ethics and usability towards third parties, such as clients, users, companies, etc. This ability is transmissible through multiple tools and techniques, among which the effectiveness of using study models as a design method (Polato, 1991) is outstanding.

According to the Project-Based Learning (PBL) approach (Kokotsaki et al., 2016; Newman, 2005), which is very important in Design, study models assume a major role in the design phase (Tonelli, 2008; Branzi, 2015), as they actually consist of the real moment of tangible understanding of the solution conceived in the mind, visualized on paper or on a screen, which has never been concretely experienced until that moment. In the same way that no one knows how to write without correcting (Nizzoli in Polato, 1991), the design process also requires that after an initial phase of formal definition of the envisioned concept, there are necessary moments of verification, which can be effectively achieved through the creation of study modelsIndeed, study models are artifacts made in the midst of the design phase as an active tool for verification and formal redefinition (Tonelli, 2008; De Fusco, 2008); what is relevant is not so much their aesthetic quality but their ability to be adherent and responsive to design needs (Polato, 1991). Their proper use, therefore, asseverates them to be an active tool in the iterative design process of refining an idea.

While in the early stages study models were traditionally handcrafted from cembran wood (Polato, 1991; Bettiol & Micelli, 2014) because it is easily machined and free of knots, to date such artifacts are mainly in other materials (paper, cardboard, polymers, foams, resins, etc.) and created partly by hand, partly through the use of digital fabrication machinery, such as CNC milling machines, laser cutting machines, and 3D printers.

This trend is a reflection of a growing attitude that leads design students to approach the ideational phase of the design journey by increasingly reducing the exploratory moment of ideas through sketches and immediate drawings on paper, preferring to move directly into a three-dimensional space, thanks to modeling software, which is increasingly popular and has intuitive interfaces. Thus, when the three-dimensional file replaces the sketch, the study model also undergoes a transformation in meaning and identity, becoming the product of a 3D printer.

This trend, which presents several issues from the point of view of theory and design practice, is steadily growing and very difficult to argue against, partly because of the rise of entry-level 3D printers (Jandyal et al. 2022; Wohlers et al., 2022), which are affordable and increasingly popular in schools and homes.

Unfortunately, when three-dimensionally printed artifacts take the place of the study model in the design phase, there are mainly negative effects, as students often self-limit themselves in devising formal and functional solutions that do not have as their only main purpose compliance with previously settled design requirements (Bolzan & Ascani, 2022; Ascani et al. 2022). Thus, the democratization of 3D printing technology (Aldrich, 2014; Von Hippel, 2005) in this specific setting means that the proposed design solutions come up against the level of knowledge acquired in the use of 3D modeling software, through which 3D printing files can be generated, which turn out to be limited and limiting, especially during the formative years of education. The same thing also tends to be reflected in the design practice of young professionals. Moreover, when 3D printers are used to shape an idea, they are rarely considered as a production technology, but rather a tool for direct materialization. In doing so, there is often a lack of understanding that objects designed for another production chain do not necessarily turn out to be correct when materialized with entry-level 3D printers, or Fused Deposition Modeling (FDM) and/or Fused Filament Fabrication (FFF) printers in general.

In observing the emergence and radicalization of this trend, therefore, we want to reflect on what might be a strategy not so much to combat it as to redirect it in a more functional way to design practice. From the premises given, it is argued how it is more interesting to maintain the dialogical and iterative dimension between the design and prototype phases, to be considered as an active moment of the design process. For this reason, thinking about Additive Manufacturing (AM) as both a design/prototypical and production tool can be a strategic element to raise an aware generation of designers, but also to try to find more sustainable applications of this technology. AM, in fact, should be considered not only as a family of manufacturing processes, but also as an enabling tool for the design workflow, with its own possibilities, limitations and peculiarities. Designing "for" and "through" AM means not only knowing its advantages, disadvantages, and principles of operation, but also questioning in an informed and conscious manner the circumstances and conditions under which it may make sense and sustainable (economically but especially environmentally) to employ this technology, which primarily uses polymeric or composite materials (leading to the generation of waste microplastics) and resins (requiring washing and curing processes with impactful chemicals).

This is why it makes sense to use AM responsibly and consciously, in a way that also fosters synergy between designers' responsibilities and the achievement of the Sustainable Development Goals (Chou, 2021). In the remainder of this contribution, we will proceed in framing how AM can foster the achievement of these goals once we truly understand the multitude of possibilities it offers, without relegating it to a tool for uncritical prototyping.

Additive Manufacturing as an enabler of Circular Design

The linear production model (Jiang, 2022), on which the industrialized production system is mainly based, although it has brought economic growth and prosperity, is no longer sustainable from the point of view of the planet's resource consumption (Sariatli, 2017). To ensure the implementation perspective of circularity, the Design is called to take on a mission of rethinking and redefining what should be the priorities when going to conceive, design, prototype, produce and use a product. Indeed, a design approach supporting linear production (Sariatli, 2017) traditionally focuses primarily on the product and how it is manufactured. In designing a new commodity, the impact of the product during its production and consumption is not addressed, nor is what happens after the product is no longer in use and is disposed of. But even before these stages, there is the design dimension that has relevant implications for the aspects of choosing the materials and technologies that should be used. For this reason, it’s quite urgent to make a change moving from design for Linear Economy to design for Circular Economy. Design in the Circular Economy is intrigue and requires a transformation in thinking, to shift 'from the current product-centric focus towards a more system-based design approach' (RSA, 2014). Circular Design seeks to produce a product or service that is useful and composed of the best materials to give the highest performance while reducing its overall negative impact (Aho, 2016).

AM technology represents an opportunity with benefits at both the product and system levels, and has a high potential to serve as a facilitator of the circular economy (Garmulewicz, et al, 2018), including the opportunity to better manage the resource consumption. There are two main features (Jimenez et al., 2019) of AM to leverage, because they not only provide significant competitive advantages but also reduce manufacturing costs:

- The geometrical complexity of the part can be easily manufactured based on the geometrical template obtained from a 3D CAD.
- The customization of the part can be simply manufactured, and products that are identical or wholly different can be obtained without affecting the process or expending additional costs.

These two characteristics of 3D printing can provide massive benefits in different applications: (1) Lightweight Products; (2) Multi-material Products; (3) Ergonomic Products; (4) Integrated Mechanisms. Referring to Lightweight Products, AM permits the production of items customized to a certain function and with customized characteristics. Some 3D printing processes can even fill a model with varying degrees of porosity without changing the material. When we consider Multi-material Products, AM enables the production of a product employing multiple materials in the same solid at the same time. This suggests that the technology overcomes one of the present weight/mechanical strength ratio constraints by introducing new functions or cutting manufacturing costs (Attaran, 2017). The components' design with AM for Ergonomic Products can provide a higher level of connection with the user by responding to the precise anthropometric features of each individual (i.e. prostheses) without necessarily influencing manufacturing costs. And lastly, AM offers the possibility of producing Integrated Mechanisms that are totally incorporated into the finished object, without the need for subsequent assembly and adjustment.

In terms of the manufacture of industrial components, the following benefits must be recognized as noticeable.

Reduction of the time it takes new designs to reach the market

When additive manufacturing is used as a manufacturing technique of the end product and not only in the production of prototypes, many of the current launch and validation phases can be drastically shortened. Another advantage is that it provides great flexibility when it comes to responding to the continuous changes in market demand.

Short production runs

The size of the production run con be minimal to the extent of being on a per unit basis while hardly influencing manufacturing costs (if and when the depreciation of the equipment is not considered). One of the characteristics that make this possible is the lack of a need for tooling, which represents a considerable advantage with respect to the conventional manufacturing methods.

Reduction of assembly errors and their associated costs

Ready assembled components can be obtained with the only subsequent operation being the quality control inspection.

Reduction of tool investment costs

Tools do not form port of the 3D printing process This represents a great deal of flexibility as regards adapting to the market and a reduction, or even elimination, of the associated costs (toolmaking, stoppages due to referred changes, maintenance, and inspection).

Hybrid processes

It’s always possible to combine different manufacturing processes In this case combining 3D printing processes with conventional processes might be interesting to make the most of the advantages offered by both.

Material consumption

Optimum usage of materials material wastage is reduced to a minimum. Any waste material can be easily recycled.

Five Design Strategies for Sustainably and Circularly using AM

In light of these considerations, and thanks in part to the great freedom in realization offered by AM, one could consider this technology as the answer to any design/manufacturing input. However, although almost any geometry can be realized through AM, it does not necessarily make sense or meet sustainability and circularity requirements when realized through the use of 3D printing technologies (Liu et al., 2016). Therefore, what are the motivations that may lead a designer to choose AM as a project and production strategy instead of other more widely used technologies?

Downstream of some observations conducted on the most effective experiences of using AM in the materialization of products, and based on previously developed experiences in prototyping in Fab Labs and research laboratories (Bolzan et al., 2021; Bianchini et al., 2019), 5 drivers were identified that can frame the correct motivations behind the use of AM in the design process: Attachment, Efficiency, Reparability, Recyclability, and Distributed Manufacturing.

Attachment

In Circular Product Design Strategies, Design for Attachment and Trust refers to the production of things that will be loved, appreciated, or trusted for a longer period of time to slow resource loops (Chapman, 2009). This is also known as "design for emotional durability": a scenario in which "people and goods thrive within longlasting empathic partnerships", it is a good method to extend product lifespan leveraging four main product meanings (Mugge et al., 2008): Self-expression, Group affiliation, Memories and Pleasure (or enjoyment).

Compared with traditional production technology, 3D Printing is very suitable for applying the strategy of implementing product personalization or making the product more unique to improve product attachment. The traditional process used to produce conventional parts and components is impacted by a series of limitations related to obtaining certain shapes, and if you want to make geometrically complex pieces, neither the mold will be very complicate nor can you get the component out of the mold tools. Thanks to 3D Printing's unique working principles, the geometrical complexity of the part can be easily manufactured based on the geometrical template obtained from a 3D CAD (Kondoh et al., 2017).

Another advantage 3D Printing brings is that the customization of the part can be simply manufactured for AM, products that are identical or wholly different can be obtained without affecting the process or expending additional costs, which means a great deal of reduction in tool investment costs. Besides, by responding to the precise anthropometric features of each individual also for medical products and prothesis, the personalization of parts is tailored to the individual needs and preferences of consumers without necessarily influencing manufacturing costs. 3D Printing makes it possible that designers, customers, and manufacturers to collaborate to create innovative products, this co-design process involves user participation in design, product simulation/certification, manufacturing, supply, and assembly processes that rapidly meet consumer needs and preferences Encouraging product attachment is valuable for a Circular Economy, it can result in product longevity, which is generally recognized as an important Circular Product Design Strategy Compared to the other strategies, strengthening the person-product relationship is that it does not require consumers' pro-environmental behavior. Once the emotional bond is built, a person will take better care of this product and postpone its replacement for his/her benefit. Infact, the strategy of increasing the product's reliability and durability to extend its lifetime is not always effective, because many products are still replaced while they are still functioning well at the end.

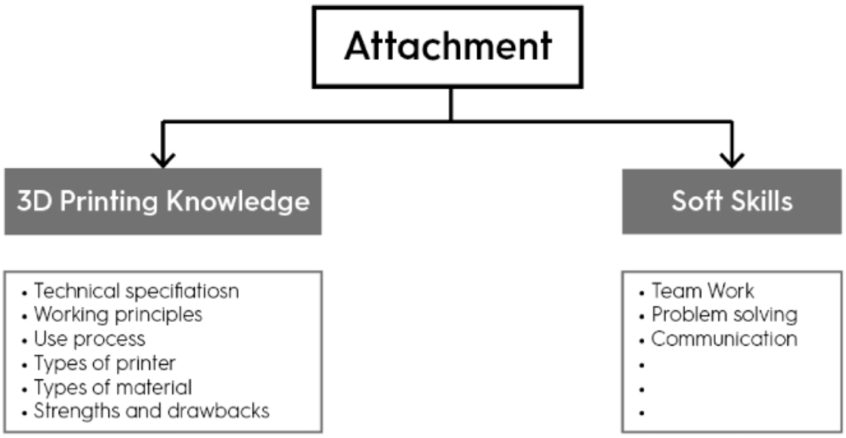


Figure 1: Attachment influence on designer.

Efficiency

AM allows the creation of complex geometries through its distinct working principles, which can lead to a reduction in material usage, part consolidation, simplified assembly lines, increased product functionality, and reduced energy consumption (Nagarajan et al, 2016). Meanwhile, the emergence of innovative generative design broadens the application bounds of 3D Printing, and 3D modelling softwares can quickly generate multiple design alternatives according to process, material, cost, and other parameter constraints, and designers can choose the best solution according to technical requirements (Wang et al., 2021). Through this automatic topology optimization a part can be optimized to a lighter and stronger structure/ yet the structure is usually too complicated and organic for traditional manufacturing methods to produce for AM the part can be easily manufactured (Rajan et al., 2022). We can conclude that AM is well suited to a lightweight design that saves energy.

The enhancement of resource efficiency can be separated into several categories.

Firstly the product development costs can be lowered by 3D Printing especially for the prototypes can be easily made to verify the design. Secondly, the low weight of the product through the optimized geometry saves the materials/ and waste materials are reduced to the minimum. Besides, the optimized geometry with enhanced structure and low weight will improve the product energy utilization performance. Thirdly, the emerging eco-design concept of Monomateriality which is building products from a single material, benefits a Circular Economy by dramatically simplifying the logistics and transaction costs of materials cycling (Chiaroni et al., 2021). Luckily, 3D printing, by its fundamental nature, inherently uses a Monomaterial to build up complex 3D forms.

In Circular Product Design Strategies, design for standardization and compatibility, and design for dis-and reassembly are preferred to recycling, as this help retain a product's economic and environmental value over time. While in this 3D Printing design strategy, creating complex yet optimized shapes encourages the designer to build a single part product that is easy to recycle and thus contributes to Circular Economy, it looks like that 3D Printing counters the traditional Circular Product Design Strategies, or if we think oppositely, Circular Product Design Strategies are enriched by 3D Printing, the complex yet mono material-built product can be recycled to become the raw material to create new designs.

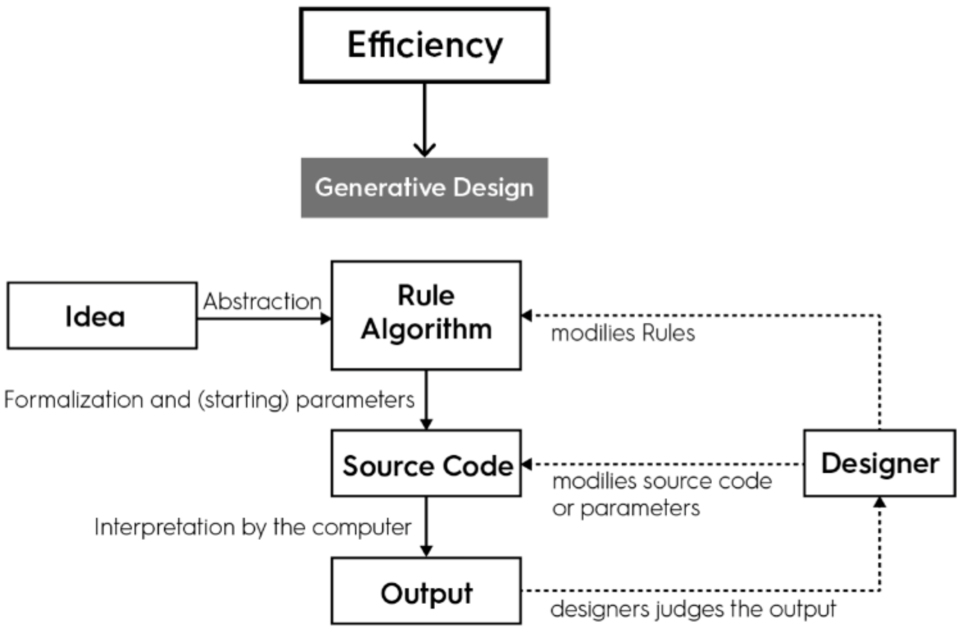


Figure 2: Efficiency influence on designer.

Reparability

Design for ease of maintenance and repair is one of the Circular Product Design Strategies, it aims at extending product life to slow resource loops. Repair is about restoring a product to a sound/ good condition after decay or damage, since 3D Printing is a way of digital production, it favors repair because broken parts can be imitated and reproduced.

For the products made by 3D Printing, the model file of the product is stored digitally and you can just produce them on demand (Mani et al., 2014), this reduces inventories and saves storage costs, making repair more accessible (Ford & Despeisse, 2016). The broken part can be replaced with the new printed one, and unlike the traditional manufacturing method, the size of the production of 3D Printing hardly influences manufacturing costs.

AM can also be very helpful for repair the products that are not originally made through a 3D printer. There are three different kinds of repair 3D printing can do. The first possibility is when the waste products can be turned into new daily necessities, the part made by 3D Printing adds new meaning to the waste and repurpose them. More easily, the damaged part can be replaced by the new 3D Printing part, besides the new part does not just fix the old product, but also add value to the new product resulted. Lastly, 3D Printing does not aim at repairing the original work, but to change the broken part into something with additional cultural/artistic value.

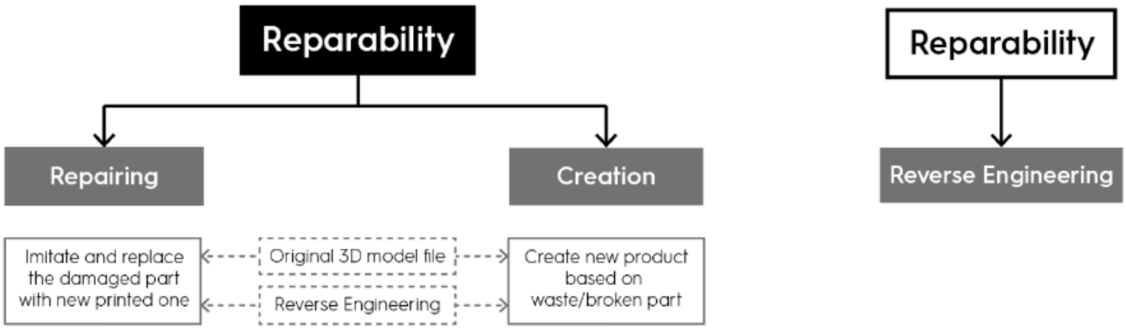


Figure 3: Reparability influence on designer.

Recyclability

For any manufacturing process, including 3D Printing, the feedstock must be formed into a state compatible with the process, and the material must exhibit acceptable service properties to perform successfully in the given application.

Materials play a dominant role in 3D Printing, particularly when considering materials for engineered structural applications. To be successful, materials must be formed into proper feedstock, have appropriate characteristics for processing in the specific 3D printer, and must have acceptable service properties (Bourell et al., 2017). So, it can be inferred that the recyclability of materials determines the recyclability of the products made by 3D Printing. As Sauerwein et al. (2019) pointed out, the recyclability of 3D Printing is extremely material-dependent. When products have very complex shapes, once they are broken, it's very difficult to repair them, and in these circumstances it's better to just replace them with new ones. When this happens, the recyclability of materials used to make the already broken products is the main priority. If the products are made from recyclable materials, they can be recycled and become the materials to produce new products, which is a good way to close the resources loop.

For now, the availability of recycled AM materials is limited, but 3D printing materials are developing in a sustainable direction, there are more and more studies being developed on sustainable alternatives for 3D printing materials, also considering the possibility offered by the Liquid Deposition Modeling (LDM) 3D printers.

In addition, advances in 3D printing feedstocks using natural derived materials have been made recently, we can directly use biopolymers like the very common PLA, or other bio-based, biodegradable, and recyclable materials for 3D printing (Liu et al., 2019), as bioplastic made from algae or with orange peels.

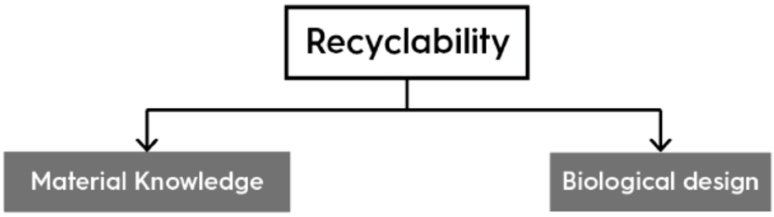


Figure 4: Recyclability influence on designer.

Distributed Manufacturing

Srai et al. (2016) define Distributed Manufacturing as the ability to personalize product manufacturing at multiple scales and locations, exemplified by enhanced user participation across product design, fabrication and supply, and typically enabled by digitalization and new production technologies. Shorter supply chains, reduced transportation, decreased overproduction through on-demand supply, and localized repair and recycling are the advantages of Distributed Manufacturing and why it is seen as a potentially sustainable alternative for centralized mass production (Ford & Despeisse, 2016). And the emerging characteristics of Distributed Manufacturing that distinguish it from centralized production are concluded as follows:

- Digitalization of product design, production control, and demand and supply integration that enable effective quality control at multiple and remote locations
- Localization of products, point of manufacture, and material use enabling quick response and just-in-time production
- Personalization of products tailored for individual users to support mass product customization and user-friendly enhanced product functionality
- New production technologies that enable product variety at multiple scales of production, and as they mature, promise resource efficiency and improved environmental sustainability
- Enhanced designer/producer/end-user participation, unlike the world of the artisan, enabling democratization across the manufacturing value chain

3D Printing supports Distributed Manufacturing since the digital file can be sent to production locally and Distributed Manufacturing can in turn solve the problems of low resource utilization and unsustainability caused by the uneven distribution of 3D Printing equipment (Howard, 2017). As the performance of consumer 3D printing improves, there is a convergence between consumer 3D printing networks and inter-organizational industrial 3D printing networks.

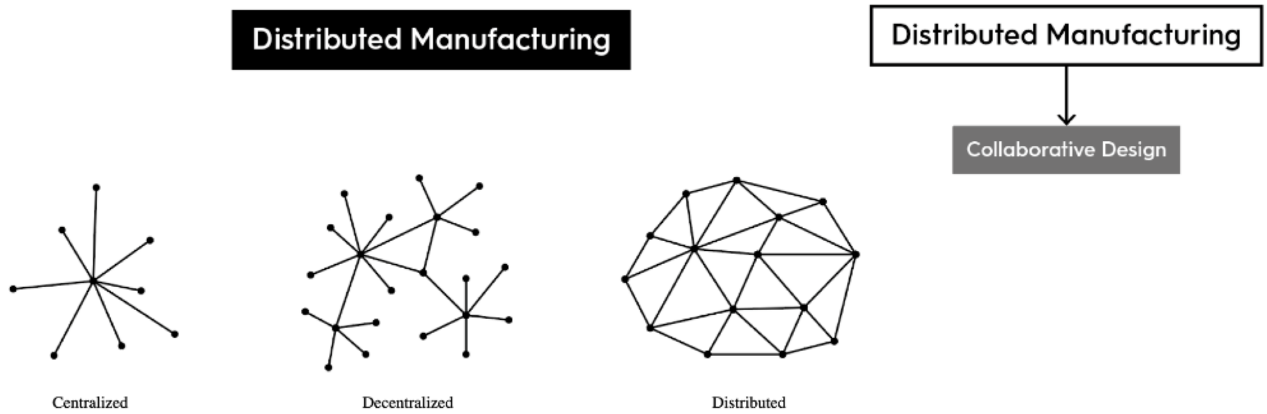


Figure 5: Distributed Manufacturing influence on designer.

Discussion

Thus, the five drivers presented can be viewed as strategies for efficient conscious and sustainable use of AM. However, they are not to be effective and functional for the activation of an AM-based circular design and manufacturing supply chain if viewed in isolation. Attachment, Recyclability, Reparability, Efficiency and Distributed Manufacturing can be functional and take on qualitative value in different design phases. In this regard, a roadmap is proposed as a graphical format in Figure 6 for better understanding and using the strategies within a design pathway that consciously integrates AM into sustainability and circularity.

Thanks to this graphical summary, it is appreciable how between the definition of the project objective and the release phase of the final result, there are the various steps of the design path that can accommodate influences brought by these strategies to go on to create effective and efficient design solutions for users, production, and environmental system.

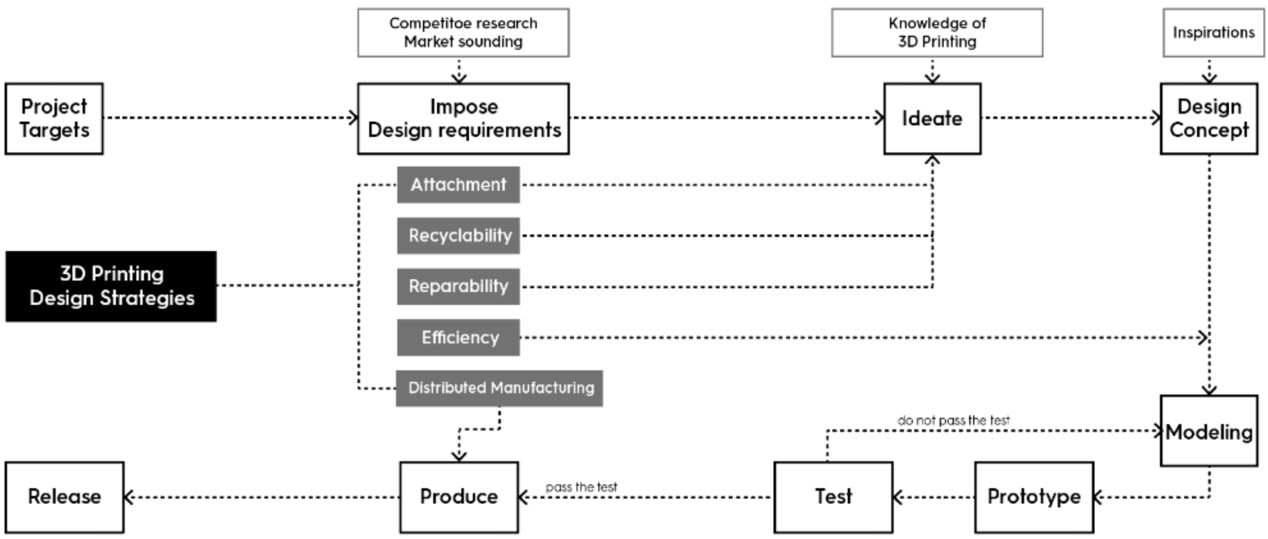


Figure 6: 3D Printing Design Strategies Roadmap

The need for specific prior knowledge

However, the identification of these strategies and their dissemination to a specialized audience cannot be considered a sufficient condition to wish that the use of AM will take place in a more conscious way and could facilitate the achievement of sustainable development goals. When one wants to convey change and expansion of opportunities, it is important to train the younger generation so that they can be active carriers of a change of pace. And in this specific case, it is important to go out and train the new generations of designers through a necessary updating of the content delivered in Design training courses.

Infact, to better make use AM, designers need to know better about 3D Printing technology, this is the prerequisite to applying 3D Printing to design projects. Technical specifications, working principles, use process of 3D printing, types of 3D Printer, strengths and drawbacks of different printing technology and so on, designers need to master the knowledge. And this is a requirement to encourage the foundation of implementing the five 3D Printing Design Strategies.

Training in 3D modeling software, understanding mechanical and physical processes, and materials knowledge are topics currently covered in the curricula of the Schools of Design. However, these topics are not functionally presented to explore the possibilities offered by AM, so students are not prepared to properly interpret additive technology. As introduced initially, they see it as an inexpensive alternative for creating study models or presenting design solutions designed for other production pipelines. Therefore, it is important to intervene in the structuring of the course of study of the Design educational realities to find the right space in which to convey structured information and skills, based on the PBL approach, in order to change misbehaviors and constitute a group of informed designer.

References

Aho, M. (2016). Designing Circular Economy. Gaia Telegraph newsletter *[referenced 26 January 2023]. Available in: http://www. gaia. fi/newsblogs/blogs/designing-circular-economy.*

Aldrich, H. E. (2014, August). The democratization of entrepreneurship? Hackers, makerspaces, and crowdfunding. *In Annual meeting of the academy of management (Vol. 10, pp. 1-7).*

Ascani, A., Cipriani, L., & Bolzan, P. (2022). PARAMETRIC MODELING FOR ADDITIVE CLAY MANUFACTURING AS A VECTOR FOR SUSTAINABILITY/CIRCULARITY IN DESIGN EDUCATION. *In ICERI2022 Proceedings (pp. 4516-4524). IATED.*

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business horizons, 60(5), 677-688.*

Bettiol, M., & Micelli, S. (2014). The hidden side of design: the relevance of artisanship. *Design Issues, 30(1), 7-18.*

Bianchini, M., Maffei, S., & Bolzan, P. (2019). Distributed design for distributed care. In Design, remix, shape, repeat (pp. 82-93). Institute for Advanced Architecture of Catalonia.

Bolzan, P., & Ascani, A. (2022). PROJECT BASED LEARNING ON DESIGN FOR 3D PRINTING ASSEMBLY. *In ICERI2022 Proceedings (pp. 4450-4456). IATED.*

Bolzan, P., Bianchini, M., Cipriani, L., & Maffei, S. (2021). Distributed design and production for distributed care. Investigation on materializing bottom-up open and indie innovation in the field of healthcare. In CUMULUS CONFERENCE PROCEEDINGS SERIES (pp. 1600-1613). Cumulus the Global Association of Art and Design Education and Research.

Bourell, D., Kruth, J. P., Leu, M., Levy, G., Rosen, D., Beese, A. M., & Clare, A. (2017). Materials for additive manufacturing. CIRP annals, 66(2), 659-681.

Branzi, A. (2015). Introduzione al design italiano*. Baldini & Castoldi.*

Chapman, J. (2009). Design for (emotional) durability. Design Issues, 25(4), 29-35.

Chiaroni, D., Franzò, S., & Urbinati, A. (2021). Digitally-enabled Circular Business Models: the role of 3D Printing. In ISPIM Conference Proceedings (pp. 1-12). The International Society for Professional Innovation Management (ISPIM).

Chou, J. R. (2021). A Scoping Review of Ontologies Relevant to Design Strategies in Response to the UN Sustainable Development Goals (SDGs). *Sustainability, 13(18), 10012.*

De Fusco, R. (2008). Il design che prima non c'era *(Vol. 6). FrancoAngeli.*

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. Journal of cleaner Production, 137, 1573-1587.

Garmulewicz, A., Holweg, M., Veldhuis, H., & Yang, A. (2018). Disruptive technology as an enabler of the circular economy: what potential does 3D printing hold?. *California Management Review, 60(3), 112-132.*

Howard, J. (2017). RADICAL TECHNOLOGIES: The design of everyday life. TLS. Times Literary Supplement, (5980), 35-36.

Jandyal, A., Chaturvedi, I., Wazir, I., Raina, A., & Haq, M. I. U. (2022). 3D printing–A review of processes, materials and applications in industry 4.0. *Sustainable Operations and Computers, 3, 33-42.*

Jiang, Z., Yuan, S., Ma, J., & Wang, Q. (2022). The evolution of production scheduling from Industry 3.0 through Industry 4.0. *International Journal of Production Research, 60(11), 3534-3554.*

Jiménez, M., Romero, L., Domínguez, I. A., Espinosa, M. D. M., & Domínguez, M. (2019). Additive manufacturing technologies: an overview about 3D printing methods and future prospects. *Complexity, 2019.*

Kokotsaki, D., Menzies, V., & Wiggins, A. (2016). Project-based learning: A review of the literature*. Improving schools, 19(3), 267-277.*

Kondoh, S., Tateno, T., Kishita, Y., Komoto, H., & Fukushige, S. (2017). The potential of additive manufacturing technology for realizing a sustainable society. Sustainability through innovation in product life cycle design, 475-486.

Liu, J., Sun, L., Xu, W., Wang, Q., Yu, S., & Sun, J. (2019). Current advances and future perspectives of 3D printing natural-derived biopolymers. Carbohydrate polymers, 297-316.

Liu, Z., Jiang, Q., Zhang, Y., Li, T., & Zhang, H. C. (2016, June). Sustainability of 3D printing: A critical review and recommendations. *In International Manufacturing Science and Engineering Conference (Vol. 49903, p. V002T05A004). American Society of Mechanical Engineers.*

Mani, M., Lyons, K. W., & Gupta, S. K. (2014). Sustainability characterization for additive manufacturing. Journal of research of the National Institute of Standards and Technology, 119, 419.

Mugge, R., Schoormans, J. P., & Schifferstein, H. N. (2008). Product attachment: Design strategies to stimulate the emotional bonding to products. In Product experience (pp. 425-440). Elsevier.

Nagarajan, H. P., Malshe, H. A., Haapala, K. R., & Pan, Y. (2016). Environmental performance evaluation of a fast mask image projection stereolithography process through time and energy modeling. Journal of Manufacturing Science and Engineering, 138(10).

Newman, M. J. (2005). Problem based learning: an introduction and overview of the key features of the approach. *Journal of Veterinary Medical Education, 32(1), 12-20.*

Polato, P. (1991). Il modello nel design: la bottega di Giovanni Sacchi *(Vol. 4040). HOEPLI EDITORE.*

Rajan, K., Samykano, M., Kadirgama, K., Harun, W. S. W., & Rahman, M. M. (2022). Fused deposition modeling: Process, materials, parameters, properties, and applications. The International Journal of Advanced Manufacturing Technology, 120(3-4), 1531-1570.

RSA (2014). Designing for a Circular Economy: Lessons from the Great Recovery. *Available in: http://www.greatrecovery.org.uk/resources/designing-for-acircular-economy/*

Sariatli, F. (2017). Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability*. Visegrad Journal on Bioeconomy and Sustainable Development, 6(1), 31-34.*

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production, 226, 1138-1149.

Srai, J. S., Kumar, M., Graham, G., Phillips, W., Tooze, J., Ford, S., ... & Tiwari, A. (2016). Distributed manufacturing: scope, challenges and opportunities. International Journal of Production Research, 54(23), 6917-6935.

Tonelli, M. C. (2008). Le sudate carte del designer. *Le sudate carte del designer, 1000-1020.*

Von Hippel, E. (2005). Democratizing innovation: The evolving phenomenon of user innovation*. Journal für Betriebswirtschaft, 55, 63-78.*

Wang, Z., Zhang, Y., & Bernard, A. (2021). A constructive solid geometry-based generative design method for additive manufacturing. Additive Manufacturing, 41, 101952.

Wohlers, T. T., Campbell, I., Diegel, O., Huff, R., & Kowen, J. (2022). Wohlers Report 2022 3D Printing and Additive Manufacturing Global State of the Industry.

Patrizia Bolzan

PhD in Design, Assistant Professor at Politecnico di Milano, Design Department, she investigates the ratio between digital fabrication (in particular additive manufacturing technologies) and Design in its practices and processes. She deals with product design system, DIY materials, functional prototypes.

Lexing Xu

Graduated in Integrated Product Design at Politecnico di Milano, he is a creative product designer, with particular experience in applying digital fabrication processes - particularly additive manufacturing - in the creation phases of new product solutions

Adaptive Materials and The Role of Design[ers] (Research[ers]) in Shaping Transformative Futures

Mariana Fonseca Braga, Imagination, Lancaster University
Adam Blaney, Imagination, Lancaster University
Dilan Ozkan, Hub for Biotechnology in the Built Environment, Newcastle University
Emel Pelit, Department of Chemistry, Kırklareli Üniversitesi
John Hardy, Material Science Institute, Lancaster University

Abstract

Imagine if our structures (buildings, cities) or objects (medical prosthetics, clothes) could be grown, self-healed and have multiple properties (shape, textures, composition etc) tuned or adapted to meet fluctuating demands. This could significantly enhance how designs can be made increasingly bespoke, reduce associated waste (financial, pollution, resources) and could begin to enable materials to be shared or flexibly utilised. The research presented in this paper aims to develop multi-adaptive materials/structures and discusses the considerable role design research can play in this developing area of research. We present our pilot project, which aims to develop adaptive material samples for medical prosthetics applications. The project involved two main research activities, material prototyping and collaborative industry workshops. We focus on the workshop findings and present a framework for determining interrelationships between material properties, responses, user demands and implications as this is key to understanding how to develop transformative material systems and how to determine what constitutes as desirable material responses/associations. From this we then reflect on our research to date to open up key questions on the role design[ers] and design research[ers] play in maximising the potential of adaptive materials and aspirations within this field.

Design Research; Processes and Innovation; Adaptive Materials; Sustainability; Collaborative Prototype Development

Biological design and fabrication processes create structures capable of self-healing when damaged as well as adapting to consistently imposed design demands. As a result, material performance is improved, and structures become increasingly bespoke or time. Importantly, these adaptive abilities are made possible because material processes maintain a discourse with fluctuating design demands, resulting in interrelationships. Meaning, the design and fabrication processes are highly iterative and flexible because of how these processes can interact with a structure's material makeup. Conversely, artificial modes of design and manufacturing, which are typically linear in nature, do not leverage these highly desirable abilities because they treat materials as inert, no discourse is maintained post-fabrication between design parameters, and material properties and there is no framework or mechanism to enable interrelationships for a material-system to be developed. As a result, significant pollution and waste (material, resources, financial) are generated because the material makeup/properties of a structure cannot be iteratively interacted with.

Imagine if we could instil these highly desirable abilities present within biology into the material make-up of our artificial structures by enabling iterative interactions with multiple material properties. In doing so, issues of waste and pollution could be addressed but also new design potentials to improve bespoke qualities. We have developed a novel design and fabrication approach, which can produce self-healing and multi-adaptive materials. Meaning, material systems can be developed that can have multiple material properties (texture, colour, composition, shape etc) iteratively updated on demand at high resolutions (e.g., molecular/granular). However, embedding multi-adaptive abilities within the material makeup of structures (prosthetics, objects, architecture etc.) highlights two fundamental challenges relevant to design research; *1) how can desirable material properties be determined for a given application? 2) How to determine what constitutes desirable material responses for a given application?* We argue that these questions are particularly important in the developing area of adaptive materials and requires a framework for determining complex interrelationships, which is especially important when conceiving bolder visions for applications, such as, growing buildings or cities capable of responding and acting as 'living' material ecosystems.

To open up this discussion, we present our ongoing research to date from a pilot project, which aimed to create multi-adaptive material samples for medical prosthetics. This involved two key research activities; 1) interdisciplinary[1] prototyping between design and chemistry and, 2) online workshops with industry collaborators. This paper focuses on the latter activity and discusses; how interdisciplinary collaboration, collaborative workshops and the role design[ers] can play in developing novel material processes to develop transformative futures, applications and platforms, which are inclusive and desirable.

Background: Framing Design Research and Adaptive Materials

Design researchers contribute to understanding real world issues and forecasting innovation through making and experimenting. In doing so, they combine creative methods and knowledge from other fields, producing 'sharable' outputs such as prototypes that enable effective communication and collaboration in transdisciplinary[2] teams by early experimentation to advance solutions to contemporary complex problems that cannot be solved anymore through linear (non-iterative) processes that utilise pre-set answers, demanding iterative test cycles typical of design approaches, crafting solutions first on a small scale to gradually increase the impact of those.

These flexible experimental design approaches and methods enable effective communication and collaboration between people with varied backgrounds and lived experiences from different stakeholder groups (e.g., experts from businesses, public sector and academy as well as citizens, 'users' or 'beneficiaries'). Making and experimenting practices throughout projects allow earlier feedback from the different stakeholders involved. These iterative tests anticipate the varied inputs, integrating knowledge beyond the

[1] Diverse knowledge areas that intersect and combine their expertise in response to a shared research interest.
[2] Collaborations beyond the academy, such as other industries, businesses, the public sector, practitioners, citizens etc.

designers' perspectives and experience earlier in the development process. As a result, these design approaches have been spilled over into different areas of knowledge and practices, from policy and service in the public and private spheres to science advancement involving transdisciplinary, interdisciplinary and multidisciplinary[3] teams and projects.

Therefore, design[ers] and design research[ers] can meaningfully address communication challenges in transdisciplinary projects that often fail due to poor communication (Project Management Institute, 2012), and because of this, can play a meaningful role in the developing research area of *adaptive materials*. Furthermore, the design phase is critical, defining most of the financial and environmental impacts of a solution although less investment is dedicated to this phase (Boothroyd, Dewhurst, & Knight 2002; Jeswiet & Hauschild, 2005; Tischner, 2000).

The challenges of defining the material specifications for a given application affect design processes as these are transformative materials which will require different inputs from the varied stakeholders impacted by the solution throughout the material's lifecycle. For example, each changeable property should be addressing a failure at satisfying not only the users' positive experience but also other desirable characteristics such as the ones related to health and sustainability that require also expert input. Hence, differences in these tuneable materials' lifecycle require different involvement from stakeholders in the development and maintenance of the 'final' transformative product when compared to standard product design that generates 'static' outputs.

Regarding material flexibility in relation to sustainability, sustainability challenges require a multistakeholder and transdisciplinary approach. In the 2000s, the interest in valuing waste grew and underpinned the ideas of industrial ecology and circular economy (Dogan & Walker 2003; Dijkema, Reuter, & Verhoef 2000). However, making circular systems work effectively presents several challenges including but not limited to the creation and maintenance of infrastructure and services encompassing a wide range of stakeholders and their interests in different industries, the public and non-for-profit sectors as well as in communities.

Adaptive materials offer potential solutions to circular systems that could be significantly independent from existing infrastructures and services that currently enable circular economy, such as recycling ones. Nonetheless, implications of adaptive material applications for design processes need to be considered beforehand to ensure they are appropriate and sensitive besides the need for further development of digital environments.

This paper sheds light into these implications through the analysis of a pilot project that explored the development of adaptive materials through prototyping, which was developed in collaboration between Design and Chemistry. Additionally, online workshops were carried out with industry collaborators to scope these implications further for medical prosthetic applications. This application was targeted because typical prosthetics do not physically adapt to any physiological changes of a patient's stump caused by multiple factors (atrophy/hypertrophy, seasonal changes, travel) (Ghoseiri & Safari, 2014), which can result in significant issues (discomfort, sores/infections) (Turner, et al., 2022). Additionally, there are specific functional demands for prosthetic (structural etc) with others being unique to a single stakeholder (shape/fit). This makes it less complex compared to a multi-stakeholder application (e.g., adaptive cities), which could have highly subjective and interconnected

[3] Different knowledge areas studying a phenomenon and bringing implications for their specific fields.

design demands. Making prosthetics a sound starting point to inform the development of multi-adaptive materials.

Design, fabrication, and sustainability

Typical design and fabrication processes reduce or even eliminate the ability of materials to have their properties updated. Hence, these typical linear design and fabrication processes generate significant waste, pollution, and resource depletion when design outputs become outdated (e.g., aesthetics, capacity, environmental, etc.) or start failing.

However, materials demonstrate the ability to update multiple properties (shape, composition, texture) in response to stimuli induced upon them (e.g., gravity, magnetism, tension, sound). These physical material abilities are evident in Otto's and Rasch's (Otto & Rasch, 1995) form-finding experiments. They demonstrate how flexible material systems for scale architectural schemes can be created by employing various material platforms (soap films, woollen threads, polystyrene chips) and subjecting them to stimuli. The 'agency' of the materials when subject to stimuli creates material systems, which enable material flexibility and discourse between design parameters and material properties. As a result, the architectural forms created can be updated and collectively tuned by varying stimuli. Furthermore, the role of stimuli to interact with, guide and 'upload' design information in active materials/biological materials is becoming increasingly evident as a strategy for new modes of manufacturing that can leverage material agency and new possibilities for design and sustainability (Ozkan, et al., 2022; Alima, 2022). This raises the question; *how can we develop flexible/multi-adaptive materials at high resolutions?*

We have developed our own approach that engages with a material's capacity to compute form and enable discourse between multiple properties and design parameters. We term this approach *'tuneable environments'* (Blaney, et al., 2019), which begins to open up the idea of circular material abilities that can be infinitely updated (Blaney, et al., 2021). The ability to create tuneable/updatable materials can contribute to tackling the challenges of extraction and addition of materials to 'new' lifecycles with linear materials that cannot change properties overtime. However, to maximise their potential for a given application there is a need to establish hierarchies and interrelationships between material properties, responses, design demands and tangible performance indicators (e.g., comfort, improved circulation, healing rates etc).

Design innovation

Design innovation can play a meaningful role in the developing field of adaptive materials within two mainstreams in which design contributes to innovation: (1) the use of design to make R&D or technological innovations marketable and suited to users (i.e., Thenint, 2008), and (2) the value of design as a 'learning by doing' process, as well as an experimental approach or a 'trial and error' practice to tackling challenges and identifying opportunities in a faster and uncertain world (i.e., Brown, 2009; Ito & Howe, 2016; Julier, 2017).

There are several design approaches to innovation. Below we illustrate design innovation approaches' flows (Figure 1).

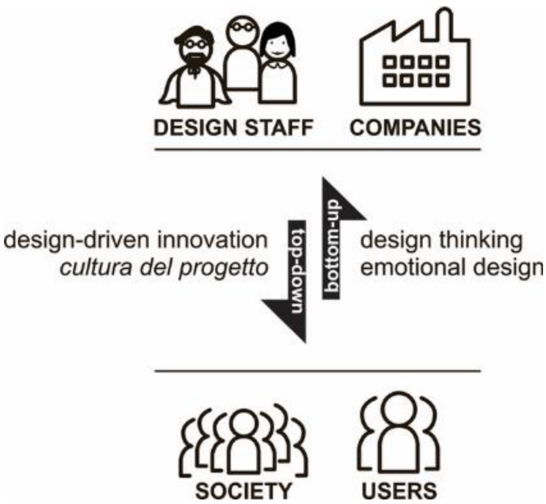


Figure 1: Design Innovation Approaches and Flows. Adapted from Fonseca Braga (2016).

Bottom-up design innovation is mostly based on and inspired by insights from users of a product, service, or system. Top-down design innovation approaches count on the expert capacity of designers to forecast trends and innovation. Both present advantages and disadvantages. For instance, disruptive innovations that are unfamiliar to users or citizens require a more top-down design innovation approach as users tend to refer mostly to prior experiences with a product, tending to generate ideas related to these prior experiences and knowledge of a product. This often leads to less innovative ideas or improvements in current solutions. Conversely, less innovative solutions, that are familiar to people, may benefit more from bottom-up design innovation approaches (e.g., design thinking, participatory design, co-design) that enable major inputs from users of a product, service, or system.

Pilot project

Our pilot project aimed to understand and develop further updatable/circular materials through interdisciplinary prototyping. The prototype set-up, our approach to interacting with materials and multi-adaptive material samples will now be briefly discussed to provide context and highlight key challenges of developing these material systems that can leverage desirable material abilities but need to be further explored through collaborative workshops.

Prototype set-up

In our current prototype set-up (Figure 2), we have developed a multi-stimuli system where heat and magnetism are modulated using a simple digital design tool (see Figure 3). This enables us to iteratively update multiple properties (shape, patterns, volume, opacity, texture etc) of magnetised plastic-like material samples at high resolutions (particle size) (see Figure 4). The plastic-like samples are melted via a heating mat, which enables self-healing when in a liquid state and can have multiple properties updated. The material updates are achieved by varying the strength of magnetism induced upon the sample by altering the height/proximity of an individual magnet as they are attached to linear actuators in a 4x4 grid.

Importantly, the ability to change the state of the material (i.e., from solid to liquid and vice versa) combined with the ability to update multiple properties opens up iterative interactions as the samples can be taken out of their fabrication environment, interacted with/hand-held and then updated or healed based on these interactions. This raised the possibility of creating structures that can become increasingly bespoke to a given user as well as their material make-up demonstrating material circularity/flexibility if the structure can be radically transformed and used for other applications. Where we see material circularity as a material that affords high degrees of flexibility and does not need to be totally recycled to radically update its properties.

The focus of this paper is to discuss how to determine desirable material response and the interrelationships between material properties and user demands for a given application. This is because the materials samples and prototyping has been documented as videos and discussed in a previous paper by the authors (Blaney, et al., 2022). To be able to determine what constitutes a desirable material response when materials are capable of multiple responses across their area/volumes and in doing so, form complex interrelationships for a given applications a framework for further prototyping research is required. For this reason, we carried out two online workshops. First with a physiotherapist from Great Britain (GB) Paratriathlon and a second with prosthetists and consultants from Preston hospital’s Specialist Mobility and Rehabilitation Centre.

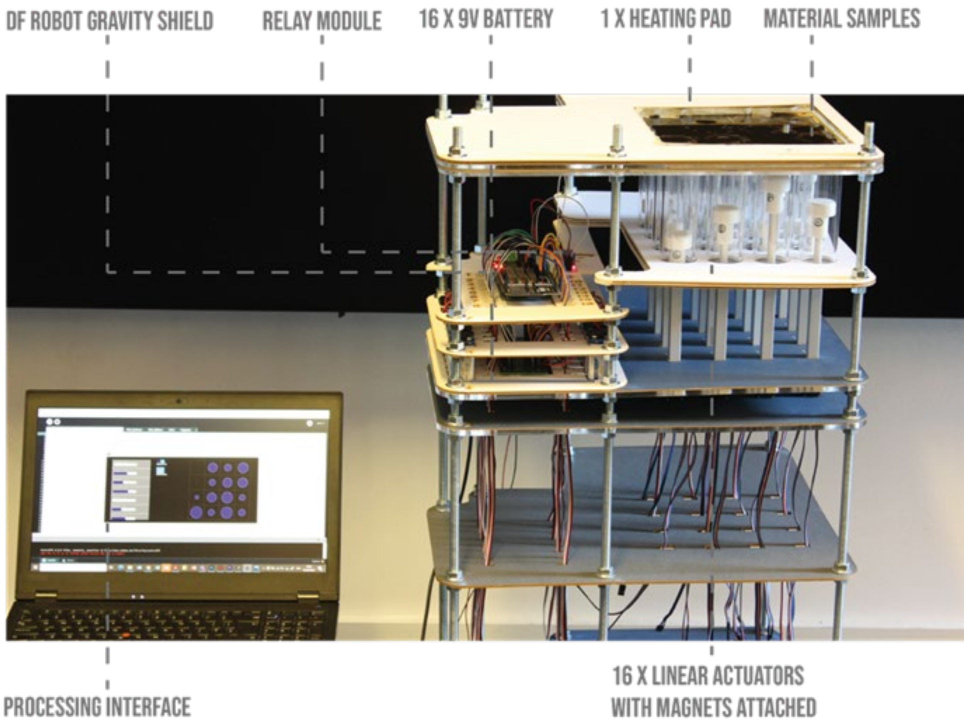


Figure 2. The prototype set-up with a material sample being interacted with.

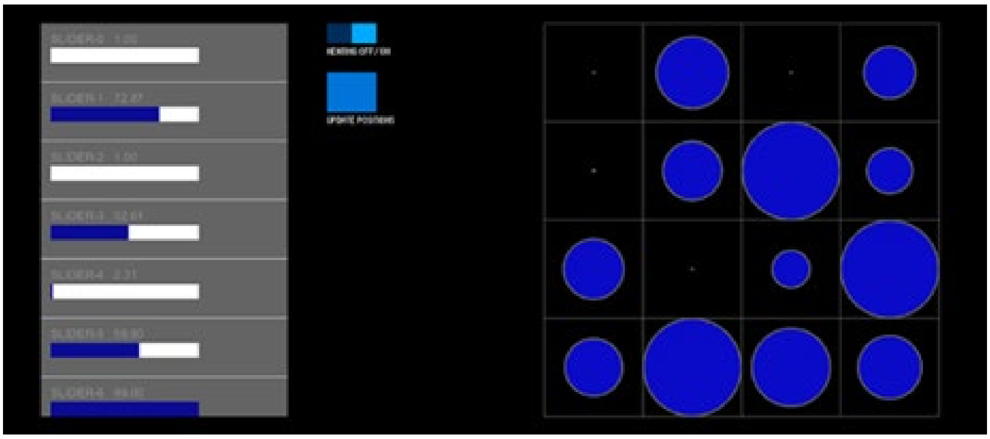
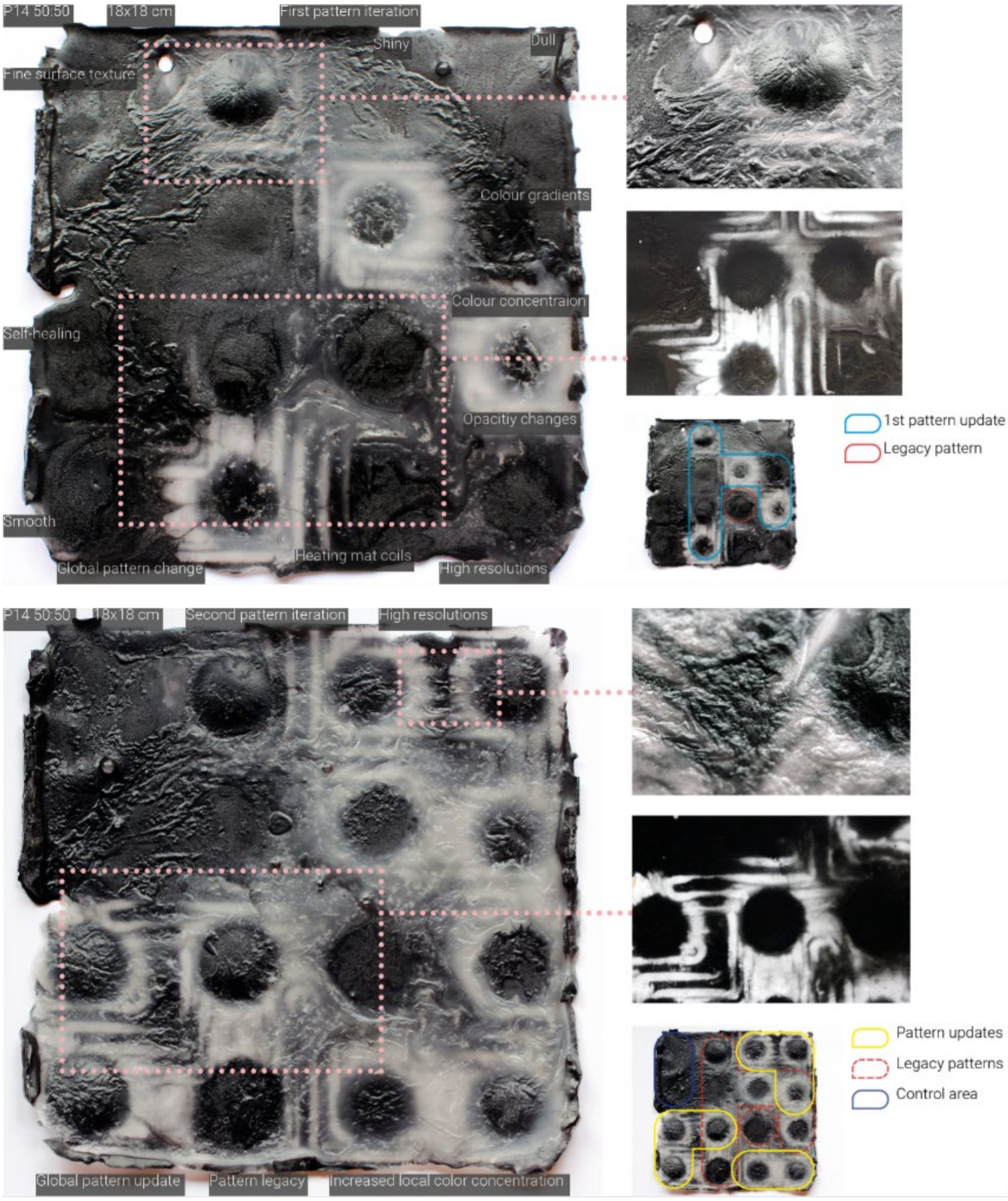


Figure 3. The parametric interface used to control material patterns.



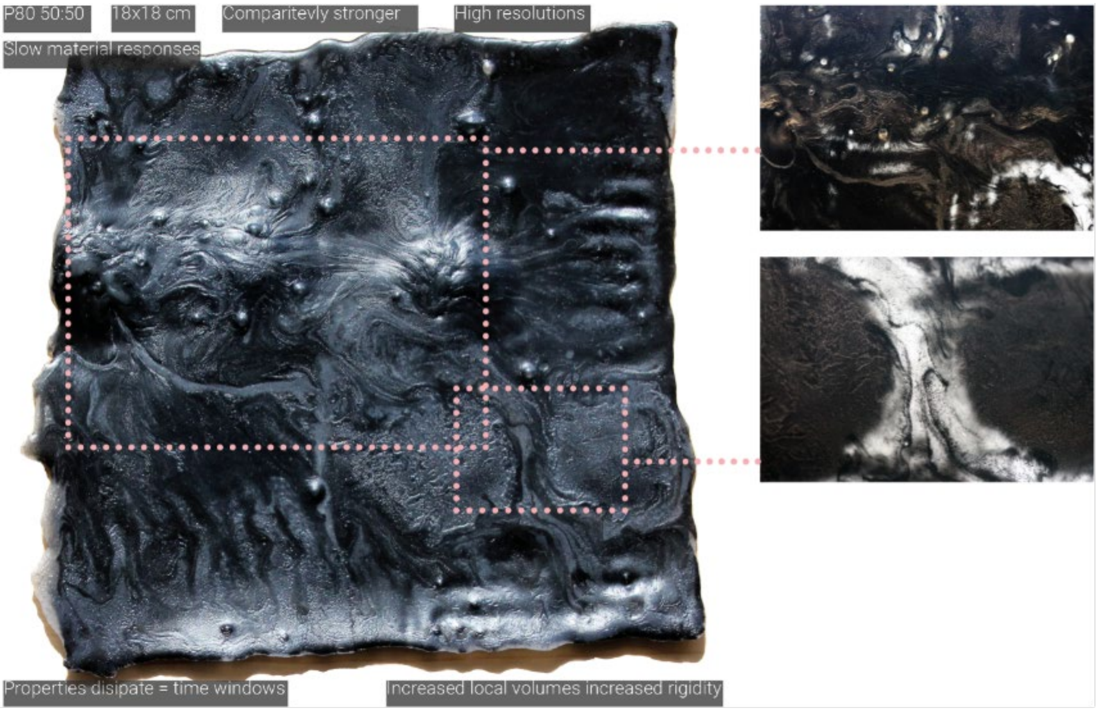


Figure 4. Material results for two material samples. The magnetised plastics enable multiple material properties to be iteratively updated at high material resolutions. The two samples have different strengths and as a result, demonstrate different qualities when interacting with them via stimuli. The annotations aim to highlight these implications and the properties generated.

Online workshops with experts

Two online workshops were conducted with experienced experts. One with prosthetists and healthcare consultants from Preston hospital's Specialist Mobility and Rehabilitation Centre who perform surgery as well as fabricate prosthetics. A second one was with a GB paratriathlon physiotherapist who supports para-athletes during competitions and training.

Each workshop lasted around 90 minutes. They aimed to capture the challenges, desirable properties, trade-offs and associations from a medical and high-performing athletes' perspectives and experiences with prosthetics.

Online templates were utilised to structure the workshop activities and capture the professionals' insights into the above-mentioned aspects.

Firstly, the pilot project and its developments were introduced to experts in both workshops to frame and make tangible the potentials of adaptive material in their field. The other topics approached varied according to the area and experience of the professionals. We described these below.

Healthcare professionals (prosthetist and consultant surgeons) play an active role in the design and fabrication processes of prosthetics. They help to define the product specifications for each patient besides following and monitoring the patient's progress during the adaptation to the prosthetics. The workshop with healthcare professionals enabled the team to understand and capture:

1_ Aspects of design and fabrication processes of prosthetics as well as how users' data are considered and applied to those, defining the product specifications.

2_ Problems and challenges of prosthetics and their effects on patients' bodies, their health-related risk, and patients' feelings.

3_ Failures of prosthetics/current materials in tackling the issues generated and areas of opportunities to improve prosthetics.

4_ Perspectives of the healthcare professionals on promising materials' response to alleviating or improving different types of prosthetics.

5_ Implications of materials that could be updated on demand for design and fabrication processes.

6_ Speculative ideas on tuneable materials applications to prosthetics (e.g., what if we had prosthetics made from materials that could be updated?) and implications for users.

7_ Desirable material responses and the types of data that need to be considered to improve patients' wellbeing.

8_ Types of amputation (bone/no bone) and implications on material systems and properties.

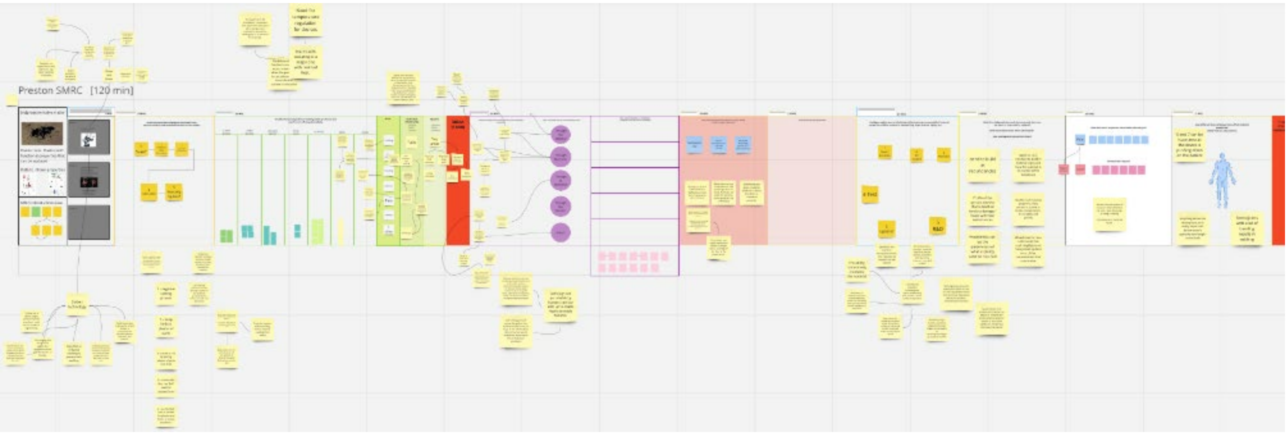


Figure 5. Online template utilised with healthcare professionals.

The workshop in the context of paratriathlon explored 8 key topics as follows:

1_ Para-athletes' data: Types of prosthetics and their impacts on the para-athletes' body parts.

2_ Effects of running, swimming and cycling with the use of prosthetics on para-athletes' health.

3_ Current management of problems and strategies to mitigate those during training and races.

4_ Types of prosthetics according to each activity (i.e., running, swimming, cycling);

adaptations during transitions between activities and desirable properties whilst switching activities; expert insight into ways of ‘measuring’/perceiving desirable properties associated with para-athletes performance metrics (e.g., running speed, heart rate, displacement etc).

5_ Current material properties of braces, prosthetics and tri-suits utilised during training and races.

6_ Types of data and potential associations to inform material responses.

7_ Desirable expert and para-athletes interaction with data (e.g., to inform materials’ updates).

8_ Future visions on adaptable abilities/properties for para-athletes' prothesis.

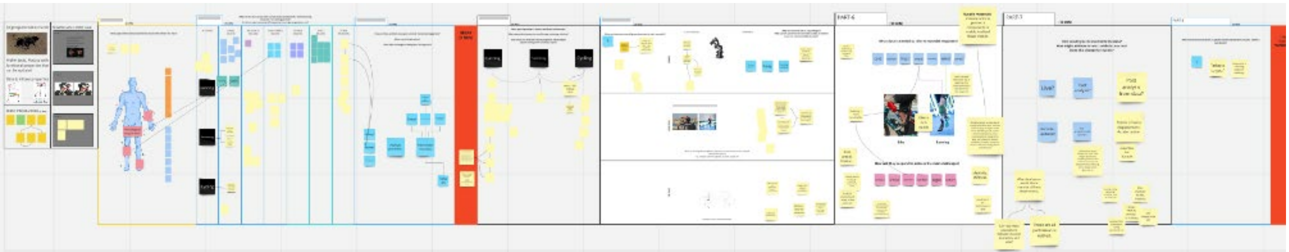


Figure 6. Online template utilised with the paratriathlon physiotherapist.

The analysis of the data collected was conducted in two stages. In the first one, the researchers identified the relations and associations between the different points made by experts and established cross-references (Figures 5, 6). In the second, they mapped the problems and explored solutions to tackling them defining also potential applications (e.g., what data/sensor would inform material requirements) (Figure 7). We present the synthesis of the data collected and of the analysis in the following sections.

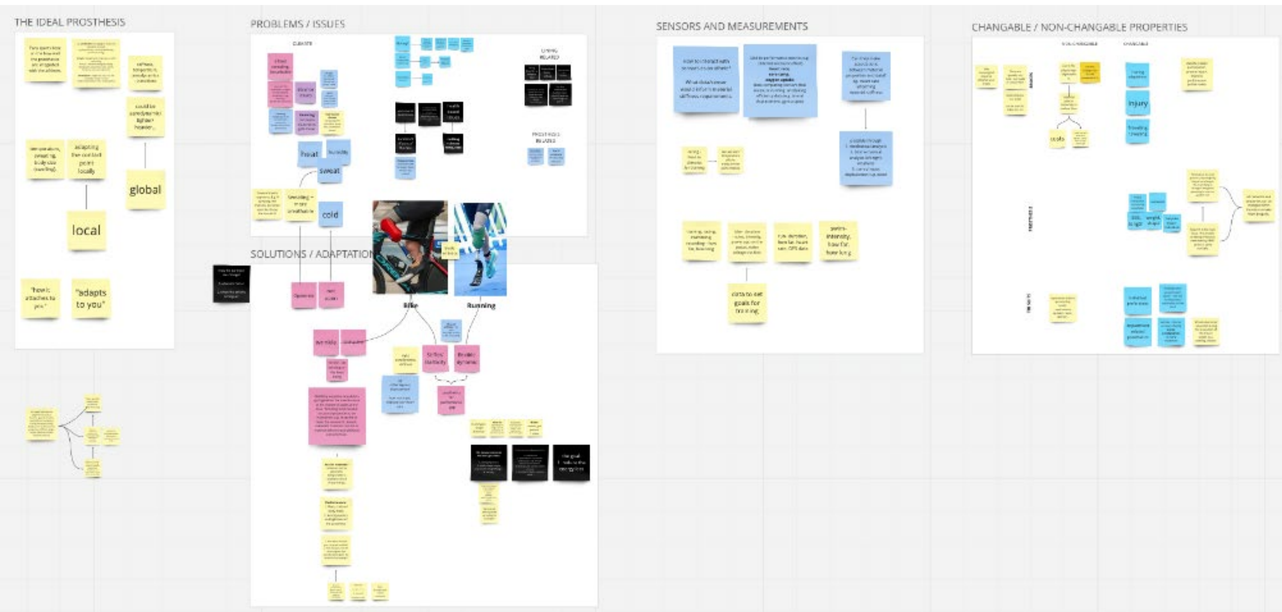


Figure 7. Example of analysis from the workshop with the paratriathlon physiotherapist.

Workshops’ results

Workshop with healthcare professionals

Existing prosthesis’ development process

Prostheses are designed by collecting patient’s data in a single-still position, using a negative casting or 3D scanning process. The data then informs the product specifications, and fabrication process begins with casting using plastic, laminated fiberglass, and plaster. All the adjustments are made manually via the prosthetist expert knowledge. The sockets created are very rigid in form, which prevents global shape-change after the final production. Also, patients need to wear silicone liners with their prosthesis (socket=glass fibre or carbon fibre, thermoplastic, cylindrical, liner=silicone). Parts of the socket and liner are made of a single material that present a single behaviour. Both lining and the prosthesis causes issues that effects patients’ daily life and are influenced by the prosthetics’ design and materials.

Current challenges of prosthetics

The materials currently applied to prosthetics do not respond to changes in the body and environment. This leads to several problems that impact people’s health and wellbeing from short to long term. We identified these challenges and their related prosthetics’ feature as follows.

While heat causes sweating and skin problems, cold leads to discomfort. The lining of the prosthetics does not adapt to the environment and body temperature changes to prevent sweating and people’s sensitiveness to cold. As a result, people can sweat, have their limb’s volume changed and suffer from skin problems such as infections and folliculitis due to rubbing of ill-fitting devices.

The volume of the body fluctuates throughout the day and with temperature changes or due to other factors such as monthly cycles for female patients. Current prosthetics’ inability to transform accordingly can lead to increase of pressure around the limb that is rubbed by the lining, affecting the body temperature in this area. Consequently, numbness can happen, fluids can build up and bursas can emerge.

Different activities cause different changes in the body’s shape and volume. The prosthetics’ connection does not respond to these changes. For example, when bending articulations, the volume and shape of the body area changes (e.g., knee gets wider and narrower during different activities). Hence, skin irritations, circulation issues, protrusions of muscle, nerves and bones can happen.

Furthermore, older adults need lightweight and structurally strong components that can be easily disconnected. Additionally, tangible feedback is necessary to confirm if the device is correctly connected to the prosthetics, which requires the deployment of advanced technology and could be useful for all user demographics.

Paratriathlon workshop

Para-athletes use different types of prosthesis during the race for cycling and running. Blade and brace type prostheses used during the race can have pin or suction attachment. Blade type is generally used for running, and its flexibility can be arranged according to the weight, speed of the athlete and complexity of the racecourse. Brace type is ideal for cycling and helps to push the peddles harder. The aerodynamics and lightness of the brace can be arranged according to the athlete's weight and comfort.

Athletes need to change their prosthesis while switching activities. Reducing the transition/changing time during the race is critical for them. Therefore, it would be ideal if their prosthetics could adapt not only to different climate conditions but also to the different activities.

The comfort of the prosthetics is a subjective matter, depends on the athlete and the condition of their tissue. Therefore, it is not possible to make ultimate claims on the best adjustments valid for everyone. However, there are also common problems that athletes face during the race and training period. These issues can be categorised according to the activities and type of prosthetics they use. Other than that, they can be related to accessibility/money, environmental, performance and health issues.

Health-based issues include sweating, balance problems, local pressure, friction/rubbing and skin irritations. They generally come from the lining, ill-fitting prosthesis, and environmental factors (climate). The performance-based issues depend on the duration and the difficulty of the race (hilly/flat). Both problems can occur when the environment is not ideal and when the athlete is suffering from fatigue.

During a race keeping the liner clean and dry is important and having a stock of liners can help the athlete. However, they are expensive, and sponsors often only help successful athletes and accessibility/affordability becomes an issue. The shortness of the material life expectancy causes environmental issues. For instance, carbon fibre degrades, loses its components and stiffness accordingly.

How can responsive materials contribute to tackling prosthetics' challenges?

Responsive materials can play a meaningful role in tackling the current challenges of prosthetics. They can change and adapt their properties to prevent the problems generated by the inability of current prosthetics' materials and fabrication processes to respond to changes in the environment and body temperature, pressure, and shape. However, to develop and define appropriate adaptive material's responses, we need a system that enables real-time data to be integrated, informing the necessary changes in those material properties. Therefore, considering the prosthetics' challenges, we envisioned the following system (Figure 8) capable of capturing real-time data from the environment and body through sensors in order to adapt and respond to changing environment and body conditions. Moreover, features of the lining's architecture can work also as structures that further facilitate these changes to timely happen.

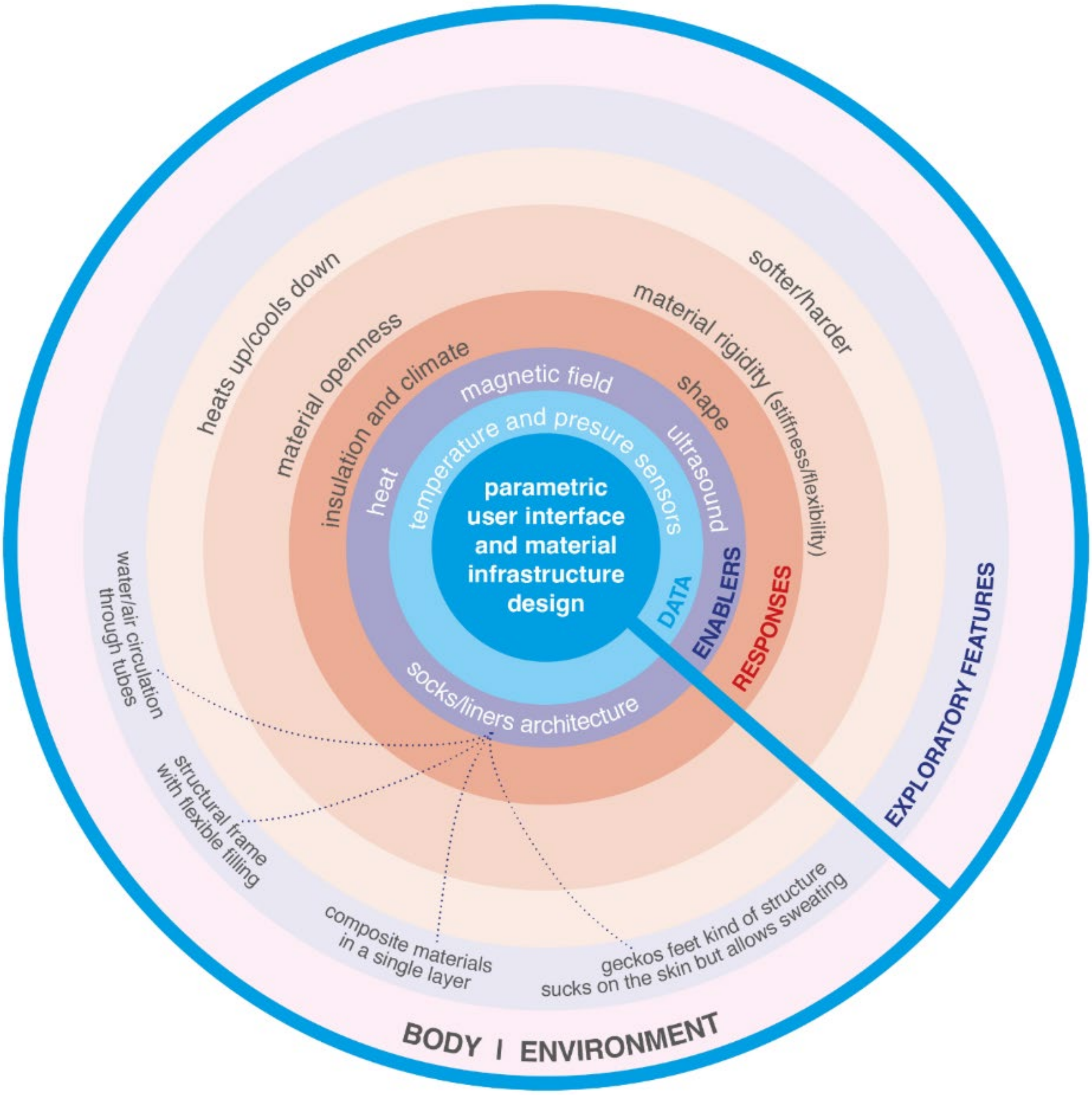


Figure 8: A parametric user interface for adaptive materials applied to prosthetics.

Additionally, the fabrication processes of prosthetics are limited in how they can accommodate varying body positions as the person moves, the diversity of activities that people will carry out as well as their intensity. Furthermore, para-athletes' prosthetics may need to be more robust due to the frequency and intensity of physical activities but still enable flexibility so they can be adapted to different activities in cases such as paratriathlon competitions and training which involve running, cycling, and swimming.

The ideal prosthetic for the para-athletes would be the one that can self-heal, respond to the race rules to become bespoke and change its material properties, size, weight, and shape according to the needs of the athlete in different activities. Moreover, responding to sweat, wind, and temperature can help the athlete to overcome their challenges.

Sweating through localised overheating is an issue for both athlete and non-athlete prosthetic users as it can cause injuries and balance issues since the prosthesis become slippery with sweat. To address this, current linings have ‘pores’/small holes to allow seat to flow to the outside of the linear and in between the socket. However, a desirable response would be to make the overall structure more breathable/porous but with current material results in a trade-off. This is because the current approaches achieve a vacuum-like fit, which provides; comfort, enables the prosthetic to be worn quickly and limits movement/rubbing between layers until it becomes wet with sweat. But it results in this overheating and the resultant issues associated with sweating. Meaning, there is a hierarchy of what is a priority with this current approach. Additionally, cycling and running needs are different, thus the rigidity of the prothesis could change according to the different activities being carried out.

Therefore, in this case, making the contacting points adaptive is even more critical. So, we suggest further sensors and an additional lining’s architecture features as follows:

- An oxygen uptake sensor and a heart rate sensor to inform tuneable materials’ openness and stiffness/flexibility.
- Potentially locating auxetic materials at locations that bend to achieve localised geometric shape-change. This kind of product architecture feature could improve comfort when move at an amputated limb’s joint. It would be desirable to position this feature behind the knee because of the change of angles at the knee when cycling. Wrinkling would make possible to maintain structural properties (e.g., shape/fit) meanwhile it would keep the vacuum fit.
- Develop a ‘geckos’ foot like material that combines soft liner layers within the structural outer layers of the prosthetic. This would enable void areas/lattice-like prosthetics and where it is in contact with the skin it can stick to it to maintain a vacuum-like fit. In doing so, it could address the trade-off issue of overheating and irritation caused by sweating because it can naturally evaporate.

All in all, a system embedding a new socket technology with adaptive materials that can also give feedback would help to speed and inform fabrication, reduce waste, be more tolerable, and open up the potential for prosthetist to remotely update a patient’s prosthetics in remote areas by reviewing data captured and sending updates directly into the prosthetic, which could improve quality of life and access to health care specialities.

Implications for design[ers] research[ers]

Design researchers and designers do not often play a meaningful role in the development of prosthetics. However, they can be key to advancing prosthetics’ innovation. Working on solutions throughout prototyping processes with adaptive materials requires designers and design researchers to anticipate not only the users’ experience and needs in order to define the changeable properties of the product/materials but the future demands for the maintenance of the prosthetics that ideally should be ‘user friendly’ or ease the users’ jobs as well as adapt to potential future needs and desires in people’s lives. The interdisciplinary collaboration between design and chemistry in this research has enabled multi-adaptive materials. In doing so, it highlighted new implications for designing with these new types of materials, most importantly; how to interact with materials across a structure’s scales (molecules to global shape), the role transdisciplinary workshops play in determining what constitutes desirable responses for a given application, and the implications of how to monitor and co-ordinated the multiple material responses generated via a range of induced stimuli over time. This ability to iteratively interact with materials enables enhanced decision-making processes by facilitating collaboration and discourse between multiple stakeholders (in the case of prosthetics; patients, prosthetists, designers, material scientists/chemists, consultants). This is because increased material flexibility is afforded along with a system that would enable faster and infinite iterations that reduce material waste and costs associated with that. Meaning, a patient can have a single prosthetic over their whole life because it can be radically altered but also finely tuned to enhance bespoke qualities.

These design innovation processes require a continuous collaboration between designers/design researchers, people who use prosthetics, heath care professionals, and other knowledge areas that contribute to advancements of adaptive materials and technologies. Therefore, the development of creating adaptive prosthetics is transdisciplinary in nature.

In this context, design[ers] research[ers] can enable better and effective communication between different stakeholder groups and can create embedded systems that make feedback loops possible utilising real-time data to inform changeable features. These exploratory, experimental and flexible design approaches are led and crafted to capture, share and harness meaningful dialogues among these groups and enable them to be further translated into the adaptive materials and technology's development.

Hence, this flexible design innovation approach utilises elements of top-down and bottom-up design innovation as both are essential to inform and advance the development of prosthetics involving responsive materials and technology. People utilising prosthetics in different conditions, contexts and circumstances are key to understanding positive and negative experiences with and features of current prosthetics. Health professionals are critical to identifying current challenges which impact the life of prosthetics' users and to facilitating associations with specific products and material features that are currently employed in the fabrication of prosthetics. Chemistry and other disciplines besides design, advancing the field of tuneable materials and technologies, are also crucial as they provide fundamental insights into materials' possibilities on the molecular level bringing implications for materials' design and helping to make the informed and imagined transformative features feasible to be experimented.

As a result of that, designers need to be capable of capturing the 'thoughts', experiences and knowledge of these different groups as well as communicating effectively with them, utilising accessible vocabulary (lay or jargon-free), being able to deeply listen and discuss possibilities of advancements in collaboration with health care professionals and these other knowledge areas (learning their vocabularies), in a continuous learning process enabled through design research that allows these exploratory and experimental learning cycles.

Furthermore, designers and design researchers provide the enabling structures and platforms for the experimentation to happen. They creatively combine technologies making structures and developing unique methods for testing these ideas. These creative processes and structures leverage future advancements with inputs from these varied stakeholder groups.

Another aspect to be considered is the openness of these different stakeholders to these design flexible and experimental approaches, understanding the value and advantages of those as well as their limitations when compared to conventional scientific approaches and methods.

Future Work

This paper outlined an initial framework and highlighted associations between fluctuating user demands, challenges with current prosthetics' materials as well as design and fabrication processes and the trade-offs and hierarchies of these. Future work will aim to expand and refine these associations/interrelationships and generate an 'interface' that enables intuitive interactions and understanding. To do this, we would develop prototypes with users to incorporate their own perspectives so nuances can be captured within the materials. Additionally, we will continue to carry out transdisciplinary research and collaborations to develop transformative material platforms/systems that can address these trade-offs through novel material properties.

References

Alima, N. (2022). Interspecies Formations: The Hybridisation of Architectural, Computational and Mycelia Agencies. PhD, RMIT.

Blaney, A., Dunn, N., Alexander, J., Richards, D., Doursat, R., Rennie, A. E. W. & Anwar, J. (2016). Coupling Self-Assembling Materials with Digital Designs to Grow Adaptive Structures. in: Doursat, R. & Sayama, H., eds. Artificial Life: 6th Morphogenetic Engineering Workshop, July 2016 Cancun, Mexico. MIT Press, pp.7-10.

Blaney, A., Dunn, N., Alexander, J., Richards, D., Rennie, A. E. W. & Anwar, J. (2017). Directing Self-Assembly to Grow Adaptive Physical Structures. International Journal of Rapid Manufacturing, 6, pp.114-133.

Blaney, A., Alexander, J., Dunn, N. & Richards, D. (2019). Designing Parametric Matter. IASDR 2019: Design Revolutions. International Association of Societies of Design Research Conference 2019. Manchester, United Kingdom.

Blaney, A., Richards, D., Gradinar, A. & Stead, M. (2021). Prototyping Circular Materials Based on Reprogrammable Matter. IASDR 2021: [_] With Design: Reinventing Design Modes. Poly U Design, School of Design, Hong Kong Polytechnic University.

Blaney, A., Ozkan, D., Pelit, E., Fonseca Braga, M., Hardy, J., & Ashton, M. (2022). 'Parametric Matter': Pushing' Updates into Materials and the Implications of Legacy and Lag. ACADIA 2022: Hybrids and Haecceities.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2002). Product Design for Manufacture and Assembly. New York: Marcel Dekker.

Brown, T. (2009). Change by design: how design thinking transforms organizations and inspires innovation. New York, NY: HarperCollins Publishers.

Dogan, C., & Walker, S. (December 2003). The best of both: A study of the feasibility of integrating scales of design and production for sustainable products. The Journal of

Sustainable Product Design, 3 (3-4), 135-147.

Fonseca Braga, M. (2016). The value of design: an issue of vision, creativity and interpretation. In P. Lloyd & E. Bohemia (Eds.), DRS 2016 Conference Proceedings, pp. 1865-1881. London, UK: Design Research Society. https://doi.org/10.21606/drs.2016.12

Ghoseiri, K., & Safari, M. R. (2014). Prevalence of heat and perspiration discomfort inside prostheses: Literature review. Journal of rehabilitation research and development, 51(6), 855-868.

Ito, J., & Howe, J. (2016). Whiplash. How to Survive Our Faster Future. New York, NY: Grand Central Publishing.

Jeswiet, J., & Hauschild Michael. (2005). EcoDesign and future environmental impacts. Materials & Design, 26, 629-634.

Julier, G. (2017). Economies of design. London, UK: Sage Publications Ltd.

Otto, F. & Rasch, B. (1995). Finding Form: towards an architecture of the minimal. Stuttgard, Axel Menges.

Ozkan, D., Morrow, R., Zhang, M. and Dade-Robertson, M. (2022). Are Mushrooms Parametric?. *Biomimetics*, *7*(2), p.60.

Petrina, S. (2000). The Political Ecology of Design and Technology Education: An Inquiry into Methods. International Journal of Technology and Design Education, 10, 207-237.

Project Management Institute. (2012). Um guia do conhecimento em gerenciamento de projetos [PMBOK guide]. São Paulo, Brasil: Saraiva.

Thenint, H. (2008). Design as a tool for innovation. Pro-Inno Europe. Retrieved from http://grips-public.mediactive.fr/workshops/view/2/design-as-a-tool-for-innovation/

Tischner, U. (2000). Ecodesign in practice. In: German Federal Environmental Agency Berlin, editor. How to do ecodesign. A guide for environmentally and economically sound design. Frankfurt: Verlag form GmbH.

Turner, S., Belsi, A., & McGregor, A. H. (2022). Issues faced by people with amputation (s) during lower limb prosthetic rehabilitation: a thematic analysis. Prosthetics and Orthotics International, 46(1). Pp.61-67.

Dr Mariana Fonseca Braga
is a hybrid designer with industry and academic experience in developing and implementing projects utilising diverse design approaches to unlock innovation and tackle societal challenges with interdisciplinary teams. She is currently a Post-Doctoral Research Associate International in Imagination Lancaster at Lancaster University with an MSc in Industrial Engineering and a PhD in Design awarded with honours from Politecnico di Milano. Braga leads research in community-led capabilities focusing on how these can feed into effective policy and technology design. Her recent publications encompass the value of design and challenges in organisations, and in tackling the UN SDGs.
https://www.linkedin.com/in/mariana-fonseca-braga/?locale=en_US

Dr Adam Blaney
is a lecturer at Lancaster School of Architecture. His research interests mainly focus on developing digital design and fabrication processes that aim to create physically responsive, adaptive and self-healing objects, devices and architectural structures. Additionally, based on principles from these prototypes, he is also interested in developing speculative visions of materially adaptive architectures and cities.

Dilan Ozkan
is an architect and researcher who focuses on working with living systems. She aims to push the limits of traditional architectural production and bring different approaches by discovering new material making processes. Dilan completed an architectural design masters at Pratt Institute in New York, where she was first inspired by the strange aesthetics of living organisms. Currently, she is a PhD student at Newcastle University. Within her research, she is investigating non-linear materials and working fungi as a biomaterial probe. She formed a study group called Mycology for Architecture to collaborate with other disciplines and share knowledge about fungi.

Dr Emel Pelit
is a researcher working in the field of organic chemistry. Her research interests are on the synthesis of heterocyclic compounds and the study of their biological activities, and on conjugated polymers. In addition, she is interested in performing organic reactions in accordance with the principles of green chemistry, using methods such as aqueous media and sonochemistry. Organic Chemistry, sonochemistry, conjugated polymers.

Dr John G Hardy
is a senior lecturer at Lancaster Universities' Material Science Institute. He is an interdisciplinary researcher with experience in chemistry, materials science, pharmacy and biomedical engineering. Hardy is interested in developing materials that interact with electricity, light and magnetism for a variety of technical applications (e.g. transient electronics) and medical applications (drug delivery, tissue engineering and regenerative medicine). He is particularly interested in bioelectronics (e.g. biodegradable conducting polymers, 3D printable conducting polymers) and biophotonics for drug delivery, tissue engineering and neuromodulation.

Constructing e-textile prototypes to inspire improvised behaviour

Lucie Hernandez, Royal College of Art

Abstract

This paper describes the construction, use and reception of e-textile prototypes and their role in generating experiences for people within or outside their usual, everyday situations. The research explores the value of co-design practices to involve community groups in creative processes and craft e-textiles pieces that can function to make technology more present and concrete for people. Participatory strategies were employed to imagine and design future contexts that people could actively contribute to as co-designers in a co-design process. The research discusses the development of the prototypes and their use as vehicles to prompt reflection in three different scenarios. The methods adopted to construct e-textile prototypes focus on integrating digital capability to highlight rich affordances for touch, emotion and feeling. It foregrounds the tangible nature of e-textiles to facilitate embodied forms of interaction and prompt actions through materials that can activate our sensory awareness.
Collaborative creative action and craft methods supported material discovery and embodied learning during the ongoing negotiation between intention, action and reflection. Findings suggest that functioning e-textile prototypes with enhanced performance qualities can facilitate consistent interactions and more playful, expressive experiences. Testing prototypes in physical, home-based spaces enabled people to appropriate them for personal use contexts, which was found to extend sensorial, perceptive and embodied awareness. The research proposes that encounters with e-textile prototypes can lead to improvised behaviour and that material combinations can play a decisive role in contributing to multisensory, lively experiences.

Craft; Improvised Behaviour; E-textile Prototypes, Lively Experiences, Design.

Introduction

This research recommends craft as a platform for material experimentation that combines computational form in the context of new textile interfaces. Craft operates in a continuously evolving, fluid space that moves between multiple domains of making to position materials in, “a set of situated relationships” (Rosner et al., 2015, p.2). Craft processes can bind disciplines and practices together, promoting play, reflection and material knowledge as critical characteristics. Rosner et. al (2015) discuss hybrid craft, the confluence between traditional modes of craft activity and computational resources that the authors suggest can, “lead to new understandings of expressivity, skill and value” (2015, p.1). Simonsen and Robertson propose that digital practices, whether they focus on material, informational, temporal or interactive forms are subject to human agency, the creation of meaning and the primacy of human experience (2013). Design researchers have described opportunities to extend physical matter (Höök, 2018), as a result of interaction gestalts that arise from combinations with computational material’s temporal form (Vallgårda, 2013).

This paper explores the methods involved in prototype construction and the value in developing e-textiles as composite forms that include technology. It proposes that participatory design methods can generate value through collaboration, shared production and co-creation, offering more accessible creative practices to people. Three contexts are presented that examine the development of e-textile prototypes to motivate an engagement with technology and encourage people to imagine technological futures that can involve them. The focus in this paper on making, using and experiencing the e-textile prototypes exposes the interrelationship between decisions and judgements enacted during a form-giving practice to influence continual refinements of the work. The final section presents the research findings and discusses forms of engagement and interaction as features of lively experiences that can emerge from encounters with crafted e-textiles.

Craft Practice

The condition of craft directs agency and skill towards the making of things. Craft practice is well positioned to understand material behaviour; a making practice concerned with, at its core, a deep, measured 'direct material engagement' (Kettley, 2012). Craft is enacted through the body as our hands and actions become the means to think. Thinking through our hands translates into skilled action, interpreting materials, making judgements and shaping the potentials of material forms. The craft practitioner David Pye asserts that risk is deeply embedded in the process, which employs, "any kind of technique or apparatus in which the quality of the result is not predetermined, but depends on the judgement, dexterity and care which the maker exercises" (2007, p.20).

E-Textiles offer an accessible, inter-disciplinary practice made up of tools and techniques that support hands-on engagement with materials across physical and digital domains. They encourage participation from a range of demographic groups as the skills are often familiar or can be learnt or shared using accessible, online resources. E-textiles prototypes support the development of soft, tangible interfaces that are well suited to experiencing multi-sensory modes to promote affordances for touch and emotion. They have been used by other design researchers such as Kettley et al (2016) and Giles et.al (2015) to explore emotional associations through sensory engagement, particularly the sense of touch.

This research relies on collective expertise and partnerships to shape and calibrate digital materials into forms that can be experiencing by people. Crafting e-textiles integrates shared competences and collaboration, especially in the production and implementation stages. Tangible creative engagement can bring technology into awareness, alongside participatory strategies to open up discussion around projected futures that people can access and actively contribute to as co-designers in a co-design process. Co-creative partnerships can contribute shared reflection and decision-making to each stage of the process. Participatory activities invite, "the involvement of people to gather insights and requirements to inform future designs" (Vines et al., 2013). In agreement with Kettley et.al cited above, one of the most powerful ways participatory practice can deliver enriching, democratic involvement is through methods that focus on direct manipulation of materials and making processes, "to imagine our possible futures" (Hartman, 2014). These practices enable people to become makers and producers rather than consumers in the move towards empowerment.

E-Textile Prototype Scenarios

This section discusses three scenarios that employed e-textile prototypes to stimulate different levels of engagement, reflection and response from people.
The first scenario presented three-dimensional textile forms that were mapped to sounds and could be activated when touched, squeezed or stroked. Multisensory, bodily engagement facilitated playful interaction and discovery to prompt speculation around future contexts of use.
The second scenario was an opportunity to facilitate co-creative processes to inspire creative engagement and form production. The focus was on the design and construction of personalised e-textiles as a chance to reflect on individual decision-making and aesthetic judgements.
The final scenario tested the functioning e-textile prototypes in domestic settings and evaluated the capacity of the pieces to inspire novel behaviour and improvised action. Each scenario was a chance to reflect on the material properties of technology as sensory stimuli, which could motivate creativity and imagination.

Introduction to the Scenario Activities

The research involved partnerships with people from multiple fields including engineers, health and wellbeing advocates and a community craft group that included volunteers, facilitators and group members. The researcher was able to leverage labour, skills and knowledge from this approach to cross-sector collaboration, to support the design and production process.

The workshops involved a local community group in Cornwall, whose members had skills in a range of textile practices and an interest but no experience of working with emerging technologies. They comprised mainly women, ranging in age from 47 to 82 and a couple of men. The group members were seeking cooperative activities that would bring purpose to their lives and enable them to create objects for people that would positively enrich their health and wellbeing. Workshops were opportunities for participants to share ideas and produce individual or collective e-textile pieces with support from a team of design researchers, artists and technologists. Activities were led by two facilitators over a six-week period as they engaged textile processes and techniques to construct individual pieces that would build confidence and group cohesion.

E-textile Prototypes as Design Prompts

Early workshop sessions with community groups were designed to introduce participants to the attributes of e-textiles and illustrate the possibilities and limitations inherent in combinations of physical and digital materials. Figure 1 details researcher constructed e-textile prototypes that used off-the-shelf technology devices to add sound effects and functionality to textiles that were stitched with conductive materials. The prototypes were used to prompt discussion, imagine future e-textiles contexts and to demonstrate material combinations. The familiar dynamic textile surfaces were designed to encourage people to actively engage, inviting touch behaviour. Activities involved touching, stroking or squeezing the textile surfaces and exploring the techniques including felting, hand stitching and digital embroidery. The surfaces were designed to be playful and support direct hands-on engagement to activate hidden sounds in the form of stories and histories related to the local area. Simonsen and Robertson observe that, "people who are not professional technology designers may not be able to define what they want from a design process, without knowing what is possible" (2013, pp.2, 36). Participants perceived the alignment between touch, sound and the tangibility of textiles, which would inform their own design decisions and aesthetic choices in their own personalised pieces. In their work with mental health participants, Kettley et al. describe the use of e-textile objects to support an understanding of the opportunities with future technology, which are made possible through the availability of tangible props (2016).

Figure 1 Early e-textile prototypes used to prompt discussion and imagine future contexts, made by the researcher.

Figure 2 Detail of cushions demonstrating the steps to layout and stitch felt pieces to interprete the nature theme, made by members of the group

Making Sound Cushions

Workshop facilitators encouraged participants to consider the kinds of objects that they could construct in the six-week schedule and the types of experiences the objects might produce. Group members were assisted to discuss and develop a creative language to represent their ideas. Combining touch with textile and sonic materials was presented as a form of tactile and visual storytelling that could trigger deeper engagement. The researcher demonstrated the capability of conductive materials to form soft electrical circuits in fabrics, which could be connected to sound and activated using touch gestures. The hands-on exploration of early e-textile prototypes described above, emphasised the ability of conductive materials to behave as switches that perform different functions. In discussion with the researcher the group proposed creating sound cushions that would provide comfort and solace for individual use. Each participant elected to embroider the surface and include conductive materials to create a touch interface to embed sound clips from nature to respond to the concept of comfort and relaxation such as birdsong, water or woodland sounds, see figure 2. The group imagined that the objects would have use applications in the home performing behaviours that were calming and involving the sense of touch with sound and visuals to construct a personal, sensory connection for people. The group speculated on groups that might benefit from the combined sensory tactile, aural and visual modes, such as people with sensory health needs, those living with dementia or children separated from their parents, see fig. 2 and 3.

Figure 3 Hand stitched cushions showing creative incorporation of conductive fabric and thread, made by group members.

Workshops were an opportunity for each group to create individualized nature-inspired surfaces that were stitched into and embellished with conductive and non-conductive materials. Earlier experiences with the e-textile prompts influenced the groups aesthetic choices and conceptual directions for their own pieces. The sensorial properties of felt and its associations with warmth, comfort and affordances for touch were clear links to the earlier pieces. The project collaborated with an engineering partner to design portable, sound devices that could be embedded inside each cushion. The devices were programmed to respond to touch events using capacitive touch capability connected to the stitched work. The components were safe and secure, easy to switch on and off and had recharging capability, see fig. 4.

The sound cushions were fully-functioning, accessible physical objects that could be played with and scrutinized in a way that is not possible on screen (Hallgrimsson, 2012). Tactile material qualities of weight, pattern and texture encouraged active exploration and sensory responses in people to encourage therapeutic feelings of reassurance and calm. The cushions expressed the flexible quality of textile surfaces that can be tailored to meet people’s sensory and psychological needs in a range of contexts. The pieces functioned as soft circuits and demonstrated computational properties including temporality and causality to extend functional, behavioural and aesthetic expressions. Technological materials generated opportunities for change that were determined programmatically and controlled through active human contact and touch gestures. During the final workshops participants stitched the cushions together, created the lining with filling and added fastenings for attaching the sound boxes using press stud fastenings.

Figure 4 Portable sound boxes are attached to the sound cushions using press stud fastenings.

Testing E-Textile Prototypes

Discussion between the researcher and the group identified opportunities for testing and validation that could be conducted with the e-textile cushion prototypes once they were complete. Members of the group expressed an interest in taking the objects home and using them for longer periods of time. The group speculated that testing could reflect on different uses in habitual situations and the potential to generate connection. The home environment was chosen as a suitable situation for evaluating use and to involve the objects in people's everyday lives. Six volunteers were involved in the validation study and were invited to use the prototypes in any way they chose for one week.

User testing is practiced in the field of HCI as a method of trialling artefacts in formal or natural settings to validate their function and performance. In this research, user testing was used to assess the benefits of functioning prototypes for personal use and analyse their value. Questionnaires were used to collect data after each trial to assess participant satisfaction, prototype performance and gather data on feelings about the object, effect on habitual activities and describe the quality of experiences. The work of Bill Gaver et al. references the interpretive relationship in design and the role of ambiguity. He suggests that offering people the opportunity to interpret a situation themselves encourages them to develop deeper and more personal relations with artefacts (2003). Playful engagement and personal interpretation were encouraged responses to the e-textile prototypes allowing participants to engage freely, without boundaries, restrictions or time constraints.

Findings

The three scenarios described e-textile pieces as research evidence and demonstrated the value of creative action for knowledge generation. Each scenario was designed to facilitate a variety of reactions, inspire participation in discussions around change, involve people in creative making or engage them in novel experiences. Reflecting on the role of material practices and aesthetic decisions to determine forms of engagement and interaction prompted further reflection as an intrinsic part of prototype construction. The decision to gather insights from validation testing enriched the reflection process demonstrating that participant behaviour and response can impact material refinements. The value of the research can be identified in the conception, construction and reception of e-textiles and the type of encounters and responses that emerged.

Prototypes were situated as propositions that could facilitate playful, expressive experiences, enhanced performance qualities and more coherent interactions for people. This research agrees with Michael Schrages' depiction of the prototype as, "medium of interpersonal interaction" that can, "craft interactions between people" (2013, p.21). The value of prototypes and prototyping moves people towards more relational, holistic appraisals of behaviour in the shift from object to experience (Schrage, 2013). The following sections present the findings that emerged from constructing and testing e-textile prototypes, analysing forms of contribution, from expert to non-expert practitioners. It discusses them in relation to participant comments and offers quotes to describe first-hand experiences relating to their construction, reception and use.

Material Practice

The e-textile prototypes demonstrated a significant role for material practice as an approach to fabricate, shape and combine physical and digital materials. For many people the tangibility of working with physical materials and using embroidery techniques was a connection to their childhoods and associated memories. For others the link to local geography and landscape were common features, which influenced memories and inspired the creative direction of the work, "I could remember the butterflies and you know the yellow of the grass and then so, yes it just sort of came". Comments from participants indicated the richness of the experience for them, "The memories it brought back, more than I imagined, worth every minute". Participants and facilitators responded positively to engaging with a broader range of sensory channels and seemed to have a richer and deeper engagement with the project as a result.

The idea that you could use thread and fabric as a conductive element in a textile object was an exciting new concept for many people. To discover these materials could be used to convey sound instigated much curiosity, one participant commented: “They have invented a thread that can connect to a computer that talks”. Participants recognised the important role for the sense of touch as an integral part of the project, “I was interested in the combination of sound and touch and feel so the whole kind of concept behind the project”.
The project facilitated hands-on making activities that allowed group participants to work collectively towards a common goal and produce something meaningful. Craft methods connected participants to others and gave meaning to people’s everyday creative activities. Greike et.al proposes, “using craft as an educational and storytelling method, to engage specific communities and facilitate social enrichment. E-textiles are not produced with commercialisation in mind, but aim to enable inclusiveness and participation in technology development or within specific disengaged or disadvantaged groups or individuals” (2019).

Collaborative Production

Crafting e-textiles relies on shared competences and collaborative production, especially in the production and implementation stages. Collaboration and co-creative partnerships can contribute shared reflection and decision-making to each stage of the process. The design researcher Matt Ratto outlines the benefits for achieving, “value though the act of shared construction, joint conversation and reflection” (2011, p.253). Collaboration and team working formed the commentary around the production of the sound cushions expanding the conception of maker and designer to include non-experts as co-creators within the work and exploring researcher roles as facilitator, designer and producer.

The workshop activities provided the team with opportunities to investigate the capabilities and constraints of participatory practice that used methods to embed people’s voices in a design process to craft technology. The project enabled people typically marginalized from technological development to be involved in “inspiring change” (Vines et al., 2013, p.2). This approach helped the researcher to evaluate the factors affecting the quality of participation, alongside highlighting the “expertise and agency of researchers who participate in design processes” (Vines et al., 2013, p.2), shape the design outcomes, and incorporate “their values in the design process” (Mörtberg & van der Velden, 2015, p.3).

Personal Appropriation and Performance

Conducting validation studies in home environments helped to evaluate the reception and use of cushions by individual participants and contributed insights into technical performance issues, personal contexts of use and forms of engagement and interaction.
Results indicated that the cushions were used in very different ways to motivate experiences with e-textiles that had personal, expressive functions, supporting meaningful behaviour for people during ordinary, everyday situations. Some of these experiences are described below and indicate the different ways the prototypes were appropriated and personalised in individual ways.

One participant described her experience of using the sound cushions in daily mediation practice as, “particularly helpful” and that the, “sound evoked happy memories and put my mind in a ‘good place’”. Another participant described relaxing with the cushion during periods of insomnia, “I took mine to bed with me and used it if I woke in the night or at early morning I had my own dawn chorus! It was very restful and reassuring”. Another participant recounted support from the sound cushion for grief consolation, “it was part of my bigger evening’s cushion hugging activity”. Their comments reference the weight, texture and design of the prototype to the experience, “the barley filling provides a solid and yet squeezable feel. The two leaves that trigger the bird-sound feel delicate and I like their golden (gold-leaved) precious feel, I tended to stroke the leaves gently to produce the bird-song”.

Technical performance issues provoked comments particularly relating to the sound quality, which tended to interrupt the experience, “volume could be higher!”, “the sound was too quiet” or participants requesting, “different sounds”. Other comments focused on battery life and size, “it’s a shame the mechanism was rather bulky as this prevented one’s head laying on it slightly”.

Sequence of Engagement

Observations and comments from the practice revealed a sequence to people’s engagement with e-textile prototypes that began with an initial encounter with physically alluring materials, patterns and surfaces and progressed to more sustained engagement. Continued engagement seemed to generate additional levels of curiosity as participants used touch gestures to discover the features of the digital effects. Experiences unfolded in different ways and seemed dependent on the interplay between the distinct materials as their properties combined, brought alive by the behaviour of participants as they explored the work. Textile engagement was immediate and familiar, and provided associations with feeling and sensation that inspired participation and connection. Deeper tactile dialogue resulted from sustained exploration and play to uncover additional layers of function and expression.

Multiple conditions affected participant reaction and response to the textile interfaces, principally the convergence of material qualities with embodied forms of interaction that relied on the body. The sense of touch was an encouraged means of engaging with the textiles and communicating the digital effects, which increased bodily immersion. Employing touch as a form of communication can bring concepts to life and represent ideas and personal memories. Giles and Van de Linden have researched the potential of e-textiles and highlight touch as a form of expression (Giles & van der Linden, 2015).

Lively Experiences

This section proposes that lively experiences can result when people are inspired to perform improvised behaviour as a result of encounters with e-textiles. This finding suggests that combining materials are performing a crucial role in contributing to multisensory, lively experiences. In this research, ‘lively’ considers the character of people’s experiences with e-textiles and recognises a definitive role for technology in extending our sensorial, perceptive and embodied awareness. The discussion reflects on, “ordinary experience in all its potential value, meaning and vitality” (McCarthy & Wright, 2007, p.79). The table in figure 4 provides a breakdown of the forms of engagement and interaction that seem to be characteristic of lively experiences.

Lively Experiences - Forms of Engagement and Interaction	
Improvised Behaviour	Encourage physical and sensorial encounters and support ‘unintended’ actions and improvised behaviour.
Interpretation and Sense-Making	Promote felt engagement and emotional responses that lead to subjective responses and meaning making.
Appropriation of Use	Support the appropriation of e-textile objects for personal use, accommodating features and functions for specific contexts.
Personalisation	Motivate the personalisation of e-textiles and prompt connection to thoughts, memories and past impressions.
Animated and dynamic	Inspire the perception of e-textiles as dynamic with animated features that merge physical and digital ‘modes’.

Embodied Contexts	Sustain embodied, tangible and corporeal forms of engagement that focus on habitual, everyday activities.
Multi-Sensory	Design for multi-sensory interaction, tangible and real-time connectivity to help communicate new meanings.
Sequence of events	Consider the sequence of events during e-textile encounters, which begins with curiosity to entice people to engage and is followed by exploration and discovery to sustain engagement.
Interpersonal Interaction	Construct opportunities for interpersonal communication to achieve mediated social relationships.

Figure 4 The forms of lively experiences

Discussion

The pieces showed that combining textiles with technological materials extended their sensorial expressions and suggested new design contexts. The inquiry reflected on the emergence of behaviour and emotional feeling in people suggesting that the prototypes had the ability to promote expressive and absorbing experiences. The research demonstrated that value can be identified in the conception, construction and reception of e-textiles and the type of encounters and responses discussed.

Research findings revealed the influence of material properties on people’s engagement with e-textile pieces and proposed that liveliness was a typical feature of combining materials to craft e-textiles. A focus on construction processes that designed the attributes of material forms had an impact on participant engagement, guiding actions and shaping affective responses. Findings presented the characteristics of lively experiences and summarised them in a table that depicted forms of engagement and interaction, see figure 4. The discussion reflected on the features of interaction and engagement although maintains that achieving deeper sensory engagement and personally expressive responses was not consistently observed. The analysis agrees with insights from Höök that new digital materials promote affordances that go beyond sensory perception, can change while in use and give rise to different kinds of behaviour (2018, p.163). This implies that crafted e-textiles that give rise to lively experiences could alter our engagement with technology towards more emotionally charged human activities and new contexts of use.

Conclusion

This research recommends craft practice as an approach to investigating the diverse combinations of material form, acquiring the skills required to make the invisible properties of computational form perceivable. As developments with novel materials increase Höök observes that it will require an approach that contributes a deep knowledge of working with materials to, “offer affordances beyond what you can touch and feel with your hands” and explore form-giving around the “interaction gestalt” (2018, p.163). Craft practice is well positioned to afford practitioners the tools, methods and knowledge to uncover material characteristics, giving form to dynamic, digital materials and shaping their properties within new and rapidly developing design spaces. Craft becomes the mode through which we can develop prototypes, generate dynamic experiences and offer material transformations that have the potential to alter our actions and behaviour in social as well as personal situations.

References

Adamson, G. (2018). Thinking through craft. Bloomsbury Visual Arts, London New York Oxford New Dehli Sydney.

Gaver, W.W., Beaver, J., Benford, S. (2003). Ambiguity as a resource for design, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. Presented at the CHI03: Human Factors in Computing Systems, ACM, Ft. Lauderdale Florida USA, pp. 233–240. https://doi.org/10.1145/642611.642653

Giles, E., van der Linden, J. (2015). Imagining Future Technologies: eTextile Weaving Workshops with Blind and Visually Impaired People, in: Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition. Presented at the C&C '15: Creativity and Cognition, ACM, Glasgow United Kingdom, pp. 3–12. https://doi.org/10.1145/2757226.2757247

Greinke, B., Sametinger, F., Baker, C., Bryan-Kinns, N., Hernandez, L., Ranaivoson, H. (2019). Social Sustainability Approaches in Electronic Textiles Crafts Communities. 3rd PLATE 2019 Conference.

Hartman, K. (2014). Make: Wearable Electronics. Maker Media, Inc.

Höök, K. (2018). Designing with the body: somaesthetic interaction design, Design thinking, design theory. The MIT Press, Cambridge, Massachusetts.

Kettley, S. (2012). The foundations of craft: A suggested protocol for introducing craft to other disciplines. Craft Research 3, 33–51. https://doi.org/10.1386/crre.3.1.33_1

Kettley, S., Sadkowska, A., Lucas, R. (2016). Tangibility in e-textile participatory service design with mental health participants. Presented at the Design Research Society Conference 2016. https://doi.org/10.21606/drs.2016.488

McCarthy, J., Wright, P. (2007). Technology as experience, 1. paperback ed. ed. MIT Press, Cambridge, Mass.

Pye, D. (2010). The nature and art of workmanship, Revised ed., repr. ed. Herbert Press, London.

Ratto, M. (2011). Critical Making: Conceptual and Material Studies in Technology and Social Life. The Information Society 27, 252–260. https://doi.org/10.1080/01972243.2011.583819

Rosner, D.K., Ikemiya, M., Regan, T. (2015). Resisting Alignment: Code and Clay, in: Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction. Presented at the TEI '15: Ninth International Conference on Tangible, Embedded, and Embodied Interaction, ACM, Stanford California USA, pp. 181–188. https://doi.org/10.1145/2677199.2680587

Schrage, M. (2013). Crafting Interactions: The Purpose And Practice Of Serious Play, in: Prototype: Design And Craft In The 21st Century. Bloomsbury, pp. 19–29.

Sennett, R. (2009). The craftsman. Penguin Books, London.

Simonsen, J., Robertson, T. (Eds.) (2013). Routledge international handbook of *participatory design, Routledge international handbooks. Routledge Taylor & Francis, New York London.*

Valentine, L. Ed. (2013). Prototype: design and craft in the 21st century. Bloomsbury, London.

van der Velden, M., Mörtberg, C. (2015). Participatory Design and Design for Values, in: van den Hoven, J., Vermaas, P.E., van de Poel, I. (Eds.), Handbook of Ethics, Values, and Technological Design. Springer Netherlands, Dordrecht, pp. 41–66. https://doi.org/10.1007/978-94-007-6970-0_33

Vines, J., Clarke, R., Wright, P., McCarthy, J., Olivier, P. (2013). Configuring participation: on how we involve people in design, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. Presented at the CHI '13: CHI Conference on Human Factors in Computing Systems, ACM, Paris France, pp. 429–438. https://doi.org/10.1145/2470654.2470716

Feeling Fabrics: Prototyping Sensory Experiences with Textiles and Digital Materials

Elizabeth Meiklejohn, Rhode Island School of Design
Felicita Devlin, Rhode Island School of Design
Caroline Silverman, Rhode Island School of Design
Joy Ko, Rhode Island School of Design

Abstract

The experiential qualities of materials play an important role in how designed products are used, appreciated and understood. Materials with pronounced visual, auditory or haptic behaviors and temporal forms can lead to engaging, multisensory interactions. However, many designers, including textile designers, currently lack tools for directly shaping these end-user experiences at the sensory level, and for understanding material experience at an early prototyping stage. With a focus on the design of dimensional, shape-changing and otherwise structurally complex textiles, we present a set of design practices and a case study in building a collection of novel materials with highly specific sensory qualities that exist both digitally and physically. Two key additions to the typical textile design workflow presented in this paper are our use of the "generalized swatch", an initial prototype that prioritizes precise multisensory description; and our usage of procedural material design software to visualize these prototypes as digital materials that can convey sensory, tactile and temporal qualities. We used a program for creating physically-based rendering (PBR) materials, popular in visual effects and gaming, to design textiles directly from the generalized swatch, in many cases without a preexisting physical counterpart. The parametric nature of this software and our workflow supports a broader role for the textile swatch, as defining a space of possibilities rather than a single design. By operating in this uniquely constrained space, where sensoaesthetic properties are predefined but the material substance, structure, etc. that lead to those properties are not, textile designers can envision material interactions at an early prototype stage and generate novel ideas for sensorially rich materials.

Textile design; Materials experience; Procedural design; Sensory design; Textile sensation and haptics

Textile-design CAD programs provide a high-fidelity preview of the design, but cannot account for the sensory and experiential qualities of the resulting fabric. At the same time, these computational tools enable the design of intricate texture, multi-layer architecture, and dimensional surfaces that would otherwise be difficult to achieve. Such textile constructions - whether knit, stitched, woven or composite - can result in unique experiential qualities, particularly the haptic effects of manipulating the material by hand. As a design team with deep expertise in designing and fabricating textiles with embedded movement and tactility, we focused our research on textiles that visually invite interaction, evoke multisensory experiences, change over time or occupy distinct states. We set out to create a framework for ideating and designing this class of textiles that privileges non-visual sensory qualities, retaining them throughout the prototyping process. Central to this work is understanding how such textiles can be formed in a digital space, where representation is typically audiovisual only. How can we transfer experiential knowledge of an existing fabric from one mode (eg. tactile) to another mode (eg. visual)? How can designers translate speculative concepts for sensory textiles into concrete prototypes?

Through this investigation, our team experimented with a range of ideation, sketching and sampling methods. The workflow we developed centers the textile swatch itself as the object of iteration and prototyping. While both material and form affect the sensorial properties of designed artifacts, we focus on the ability of materials to elicit "freestanding" sensory experiences in the absence of familiar forms or product usage activities. The way an individual interacts with a textile sample is significantly different than a garment or upholstered furniture: our explorations in unstructured material discovery revealed a wide range of interactions, and resulting embodied effects. With this approach, the design vision consists of a set of experiential qualities, and the prototype is an approximation evoking those qualities , which can be continuously refined. Our prototypes take one of three formats: a "generalized swatch", which directly describes the intended experience at the outset of the design process; a physically-constructed fabric, or a procedurally-generated digital material, which actualizes described traits into a physical or virtual form. These methods enable designers to declare an intended experience - of encountering the hypothetical material - and subsequently determine its formulation and fabrication. Reverse-engineering a textile from its intended sensory qualities can be a powerful technique for designers to create highly stimulating or finely tuned multisensory effects, especially those that engage with senses beyond the visual. The generative and procedural methods outlined here support the creative process by opening up the design space to exploration and improvisation, broadening possibilities for new material designs and experiences.

Background and Precedent Work

The body of research on materials experience (Giaccardi & Karana, 2015) informs our approach to characterizing existing multisensory materials and developing new ones. At the perceptual level, material properties are often described by rating on scales such as stiff/flexible, warm/cold, light/heavy, and rough/smooth. Resources such as Ashby diagrams (Ashby & Johnson, 2002) allow designers to select materials by comparing them along two axes, typically physical measurements. Mapping the sensoaesthetic properties of materials in this manner can identify ways of modifying materials to produce specific traits (Miodownik, 2007). Frameworks including the expressive-sensorial atlas (Rognoli, 2010), experience map (Camere et al, 2015) and experiential characterization toolkit (Camere & Karana, 2018) demonstrate relationships between material properties at several levels. Camere & Karana (ibid) note that combinations or contradictions at one level yield qualities at a different level: a material that is hard yet soft (sensorial) can be surprising (affective). Many current material mapping methods use unipolar or bipolar scales that position such properties as opposites, overlooking the interesting, uncanny results that can emerge when they coexist in a material (Veelaert et al, 2020). This insight is especially relevant to our work, which seeks out novel sensory experiences that both physical and digital textiles can evoke. Imbuing a material with affective qualities (eg. surprise) through sensory contradiction requires unique methods in digital space.

The growing prevalence of digital textiles in the design process and retail settings raises questions about how to effectively convey fabric handfeel. Atkinson et al (2013) showed that characteristics like roughness and stiffness could be inferred through touchscreen manipulation of interactive textile videos. Temporal form is key in communicating these physical properties, and can also provoke emotional and embodied reactions: participants who observed fabrics moving with distinct choreographed rhythms attributed to them a sense of aliveness and narrative (Vallgårda et al, 2015). In scenarios where touching a fabric is impossible visuals and movement heighten the sensory experience. Designers working in digital environments can utilize these dimensions, for example creating visualizations of physically implausible material behaviors to mockup interactions (Barati et al, 2017). Citing Edelkoort's (2012) notion of "super tactility", Petreca (2017) asserts that a virtual textile need not attempt to recreate physical fabric, instead balancing realistic qualities with the "imaginary and the emotional". We use procedural design software to prototype fabrics that convey experiential qualities through their appearance and range of possible states, leveraging the virtual textile as a vehicle for sensory experience rather than a representation of an existing fabric.

We engage with the textile swatch in the context of its typical use, critiques and proposed alternatives. In textile design, the swatch is a small sample that functions as a "promise and a possibility" of its counterpart, a large quantity of fabric yardage (Igoe, 2020). The swatch represents a finished design but leaves much to the imagination, convincing designers and consumers that the material it represents can appear as they envision it. Laughlin (2010) calls this underdetermined nature "the tyranny of the swatch", instead proposing the material-object, an intersection of material and form, as a type of sample that foregrounds sensorial qualities. While a typical use of materials libraries is comparison, a single material's range of expression can also be evaluated, eg. by molding it into a series of forms that yield different sensorial properties (Wilkes and Miodownik, 2018). Material samples that change over time, such as mycelium-based composites (Parisi et al, 2016) and textiles that respond to environmental conditions (Talman, 2019) similarly support the notion of the swatch as a space of possibilities. These expanded definitions of the swatch enable it to act as a prototype, a malleable idea of what a material could be.

Our research methods draw upon precedents such as experience prototyping (Buchenau & Suri, 2000), experimentation as improvisation (Douglas & Gulari, 2015) and material tinkering (Parisi & Rognoli, 2017; Rognoli & Parisi, 2020). We began this project with hands-on material exploration, inspired by recent research into ASMR as design inspiration (Klefeker et al, 2020) and the idea that unstructured play can yield valuable insights. A broad palette of interactions and gestures promotes discovery of sensorial and affective qualities, especially when the individual cedes control to the material (Cary, 2013; Aktaş & Groth, 2020). The influential textile designer Anni Albers advocated for a similar type of "active play" to spark creative impulses and restore understimulated tactile sensibilities (Albers, 1965), a sentiment echoed in present-day material tinkering and material activism (Rognoli & Ayala Garcia, 2018). Our team used these principles in the information-gathering stage and while developing new material concepts that embody gesture, movement and multisensory effects.

Methodology

Capturing textile behavior

Identifying and describing textile behavior was an important precursor to developing a workflow for multisensory textile prototyping. Our prior work designing and fabricating dimensional textiles with textured surfaces served as a starting point for identifying the sensory qualities of fabrics. Using these samples, we experimented with a range of interactions between body and textile (eg. twisting, squeezing, resting, stroking, enveloping) and documented the results with video and written annotations. Video was particularly important in identifying haptic qualities: while a fabric's surface texture cannot be fully represented visually, the audio cues that result from interacting with the surface, and the motion of a hand moving across or pushing against it, provide implicit clues about its physical properties. At this stage, it was important that we subject these fabrics to a wide set of actions not limited to typical uses of textiles. While some, like sitting on or wrapping oneself in a textile, are reminiscent of furnishings or clothing, others, like folding a thick, compressible sample upon itself or swaying a fabric suspended in midair, position the textile as an object of investigative play.

Figure 1: Stills from video documentation of textile interactions that captured a range of gestures.

Moving from these specific samples towards a generalized method of capturing and communicating textile behavior, we gathered descriptive words from our written annotations, industry-specific and vernacular terms that reference the auditory, olfactory and tactile properties of materials. Many common textile-industry terms act as similes or borrowed language, describing a fabric as "peachy", "sandy" or "soapy"; while it might be surprising to encounter a fabric that feels like rough sand, the experience of touching its surface is effectively communicated through comparison. Likewise, everyday words like "silky" and "fluffy" use fibers and textiles as a reference point from which non-textile materials can be understood. Another subcategory that we identified as useful in prototyping sensorially rich materials is onomatopoetic terms, such as "buzz", "hum", "crinkle" and "thump". These words, whose phonetic pronunciation closely aligns with their meaning, suggested a way of translating sensory experiences synesthetically. If reading a word evokes the sense of touching a familiar material and hearing the sound it makes, a deliberate grouping of multiple terms may suggest an idea for an entirely new type of material, for which a frame of reference and prior experience do not exist. We proposed that materials can also be onomatopoetic if the way they look is consistent with how they sound and feel. Such "cohesive" materials, like smooth, lustrous silk, are distinct from "contradictory" materials, like a quilted fabric that is bulky yet ultralightweight. When physical properties are surprising or concealed by material appearances, uncanny or impossible-seeming sensations can arise. Collecting words and phrases from disparate sources enabled our next phase of experimentation, in which we combined several general terms to narrow their broad meanings into a specific material idea.

Figure 2: Selected sensory terms.

Text-based ideation

Working with language as a building block for material ideation can provide unique insights. Textile designers often begin the creative process by compiling visual reference material, including fabric swatches, colors and images, that inform the conceptual, aesthetic and material qualities of their work. We adapted this strategy by using textual descriptors as movable units that add connotation and specificity, forming an as-yet imagined material. Each time a word is added to a group, it narrows the space of possibilities of how that material might be realized. A term like "fluid" is broad and could describe many diverse materials, but a grouping like "fluid, sleek, abrasive, pliable" conjures images of a particular material that may vary depending on the designer's experiential knowledge of material behavior. "Fluid" and "pliable" seem to contradict each other, as the latter implies a higher level of hardness in a substance that can be molded with some effort. Does the material look fluid (like polished metal or plastic) but feel like soft clay, is it made of movable folds of a silky fabric like charmeuse, or is its handfeel dependent on factors like thickness and temperature? Each potential resolution of the apparent contradiction is a specific material design, in which known or hypothetical fabrication strategies and ingredients are combined to produce a result aligned with the text-based prompt. In developing material ideas from language, we acknowledge that the structure of this workflow bears some resemblance to currently available text-to-image AI applications, in which the user enters several words and an image is synthesized from their meanings and contexts. In these cases, the image is the final product, neither a prototype nor a tangible design for a material. Our process utilizes language to provoke design ideation: crucially, the designer must determine how each term is embodied by the material, making unique choices based on prior knowledge or subjective opinion. This results in a sensorially specific prototype, representing a space of possibilities not yet reduced to a single idea, from which refined material designs can be developed.

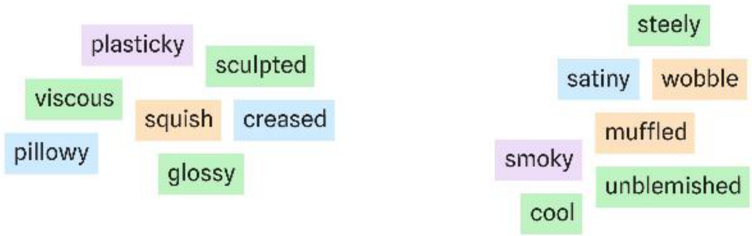


Figure 3: Examples of text-based groupings created to define new material designs.

Semantic ambiguity allows sensory terms to build increasing specificity when layered in this way. Words relating to human-material interactions, like "squish" and "thwack", can describe sound, handfeel or appearance, depending on context. They may indicate a material's tendency to react (produce a certain sound or haptic feedback) when manipulated, or describe the *expectation* of sensory feedback that a material elicits based on its appearance, ie. the type of interaction that it invites. In the context of a group of descriptors, the ambiguity of such terms is resolved, describing a singular material experience. This approach to building specificity through grouping is distinct from typical textile design processes, in which images and existing materials are combined into reference-objects for creative outputs: these can unintentionally constrain design choices to the space of colors, finishes and constructions found within the references themselves. Our method also differs significantly from technical textile creation workflows, in which the physical properties of the fabric are specified at the outset. In these scenarios, fabrication methods are determined early on, and iterations in structure or raw-material type are assessed quantitatively rather than sensorially. By using words as references, accompanied by abstract or ambiguous imagery, we preserved two goals central to our methodology. First, the sensory experience inherent to a material is at the forefront, described by words that engage with multiple modes of sensing. Second, we avoid focusing on textile fabrication strategies or raw materials at this stage, allowing previously unimagined or underexplored material creation methods to emerge as the designer considers the qualifiers and constraints. The logical/associative process of determining a material's makeup in this way may lead to novel or hybrid swatches, reverse-engineered from their own descriptions. Our process shifted between specificity (documenting existing fabrics) to generality (accumulating sensory descriptors) back to specificity (creating complex/contradictory groupings). This way of prototyping allows concrete ideas to emerge that are not directly derivative of their precedents.

Building a collection of multisensory materials

Figure 4: A collection of materials developed using this methodology. The title of each material is derived from its generalized swatch, a prototype format that leads to subsequent digital and physical iterations.

To design a collection of novel materials with highly specified sensory properties that exist in both digital and physical space, we looked to procedural material creation for its capacity to preserve and amplify features relevant to materiality and sensory experience. We utilized Adobe Substance 3D Designer, a program for creating physically-based rendering (PBR) materials popular in visual effects and gaming, to realize material concepts that emerged from initial text-based and generative exercises in the framework of a "generalized swatch". In design practices, the swatch is a small, rectangular material sample that serves as a reference. It is useful to designers in the prototyping phase but is not itself a prototype: the material has already been designed, refined and possibly even manufactured, and is not open to further changes. Related concepts in textile design, such as the sampler or sample blanket, include many copies of the same material subjected to different processes (eg. washing, bleaching, dyeing) or constructed with different parameters (eg. different threading sequences on a loom, which produce pattern variations). These examples demonstrate a greater degree of flexibility regarding the fabric's final form by permitting multiples of the same basic unit, the swatch, to exist side by side. It's implied that one variation will be selected as the final design, locating the sampler at an earlier stage of the design process than the swatch and allowing it to function as a prototype of what the material might become in many parallel instances. We took inspiration from this format for representing fabrics as potential outcomes, and coined the "generalized swatch": a cluster of text and images that form the boundary of what the material could be. The generalized swatch is distinct from a design brief or request for development in that it intentionally underspecifies details that designers use as starting points. It does not contain explicit directives about colors, raw materials or fabrication processes; instead, it describes the visual, auditory, tactile and olfactory qualities that the eventual material will possess, or the sensations and resemblances it may evoke, asking the designer to reverse-engineer it from these outcomes. For example, a generalized swatch may assert qualities like "dense", "rubbery", "ooze", "thwack", raising the question: what sort of material might behave and be perceived in such terms? In this way, it acts as a prototype, preserving the openness that exists at the beginning of the design process by prompting the designer to think abstractly and associatively. This first draft of the material, which lacks concrete representation but is nonetheless precise, leads to subsequent prototypes rendered in physical and digital form.

Figure 5: A generalized swatch includes text and images that describe experiential qualities.

When moving from the generalized swatch towards tangible prototypes, we identified two potential workflows for material creation. Because a core goal of this project was to demonstrate the sensory potential of newly designed materials in physical and digital space, it was important to establish methods by which both versions of the material could be created, coexisting and informing one another. The order in which these parallel prototypes were created was particularly important, as designers of physical fabrics often use immaterial references as guidelines and vice versa. We recognized that the first material sample would inevitably influence later samples, visually clarifying details to emulate or diverge from. This led to two complementary workflows: (1) a physical-first workflow, in which the generalized swatch guides selection of raw materials (eg. yarn and fiber) and fabrication techniques (eg. loop-pile knitting) in the creation of a physical sample, and (2) a digital-first workflow that bypasses fabrication constraints and distills the text- and image-based prompt into a procedural material (eg. a biomimetic cellular pattern) with flexible parameters.

Physical-first workflow

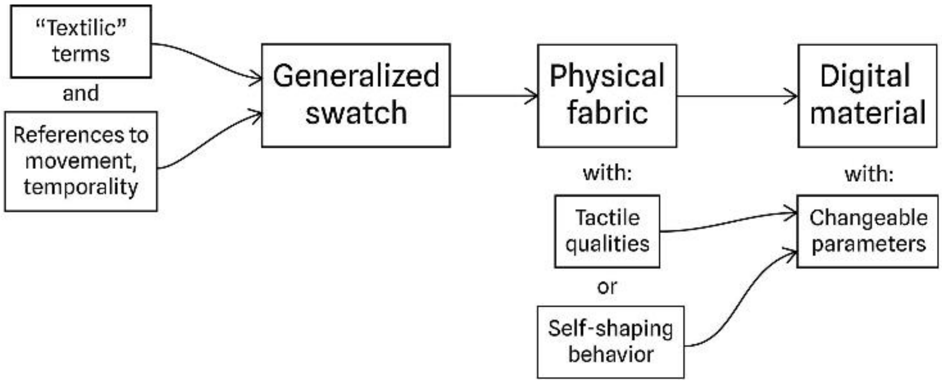


Figure 6: Diagram of three kinds of prototypes generated from the physical-first workflow: generalized swatch, physical fabric and digital material.

Before initiating this phase of work, we established criteria for deciding which approach would be appropriate for each generalized swatch in the collection. The first approach, which is related to typical textile prototyping, is suitable for materials whose experiential qualities can be directly connected to a specific textile technique. Generalized swatches that included descriptors like "prickly", "stiff" or "scrub" were more immediately evocative to the textile designers on our team. Such terms suggested fiber-based constructions, like short, coarse yarns protruding from a fabric's surface that feel scratchy when brushed. An early test of this workflow was done with the generalized swatch "sandy staticky buzz", which included references to small-scale, high-stimulus phenomena: glitchy, grainy, irregular patterns and textures with many points of contact. We identified loop-pile knitting as a technique that distributes small segments of yarn across the surface of the fabric, closely matching the white-noise qualities of the generalized swatch. Overtwisted linen yarn was selected for its tendency to twist back onto itself and form small, dense bumps in the fabric, ideal for a highly textured "sandy" handfeel. We characterized this design as onomatopoetic, as its scattered visual pattern evoked how it felt to touch its fine-grained bumpy surface.

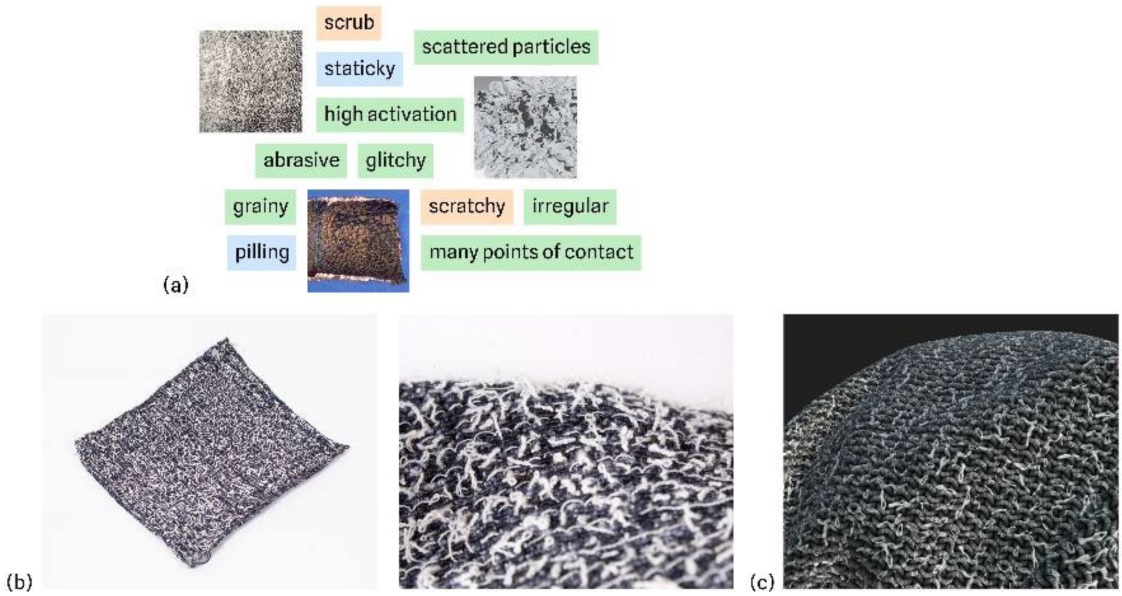


Figure 7: The generalized swatch (a) informs the knitted prototype of "sandy staticky buzz" (b), which is then used as a reference material to develop a digital material in Adobe Substance 3D Designer (c).

This process of translation from sensory terms to relevant textile techniques is a movement from generality to specificity, filling in many of the blanks (what is this made of? What equipment is used to make it?) so that a singular material can be created. In this method, the physical swatch is assessed for its adherence to the sensory qualities expressed in the generalized swatch. It is then used as a visual/tactile reference object when creating a procedural material, which may be an improvement upon it or simply an alternate manifestation of the same material qualities. Characteristics like the shape of knit stitches, the twisting of yarn loops, and the colors of variegated yarn would be highly challenging to model from imagination, and doing so would miss the point of this workflow altogether. As textile designers, we know that these small details of the fabric's construction are integral to how it looks, sounds, feels and moves. Using the physical swatch as a source of information for the digital swatch not only enables a higher level of realism in the digital material ("this looks convincingly like a fabric"), but also embeds specific haptic qualities ("this material looks like it would feel sandy, and make a scratchy noise when manipulated by hand"). The fabric's visual and physical features can be rendered by the digital material's base color, heightmap, roughness and other channels, suggesting a complex sensory profile.

Digital-first workflow

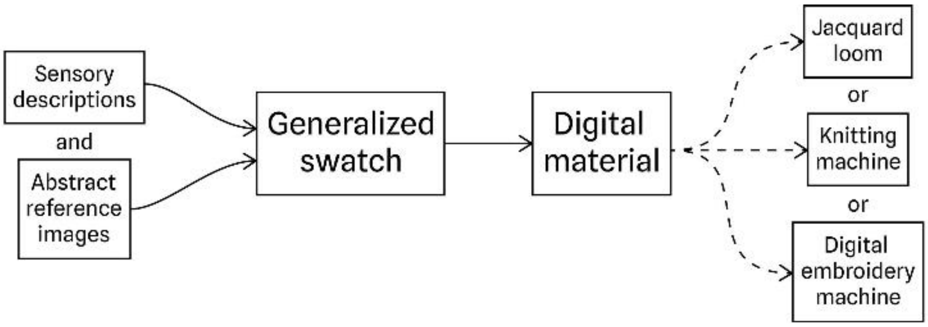


Figure 8: A digital material is generated first in this workflow, which then informs a physical fabric that may be made in a variety of ways.

In the second workflow, the terms of the generalized swatch feed directly into procedural, rather than physical, material-making. This approach is suitable for materials whose "haptic interest" is derived not from textile structure but from broader qualities like reflectivity and smoothness; those with contradictory pairings of terms, such as "stable / gooey" or "fluid / fractured"; and those whose descriptors suggest a biological or immaterial phenomenon, like the refraction of light, rather than a deliberately constructed textilic artifact. We characterized these materials as "at home" in digital space, not belonging to a specific textile technique, in part because of their uncanny qualities. Working in a digital-first way, without fabrication constraints, allowed us to visualize the physical improbabilities built into certain generalized swatches. The PBR materials that we created are somewhat illusory and fictionalized, since they depict the outer surface of a material in great detail but don't comply with the rules for how knits or wovens are actually constructed beneath the surface. A greater level of improvisation and freedom is thus possible, with procedural methods enabling instances of tinkering or "bending" the material past the point of realism. The ability to quickly visualize a speculative material, in higher fidelity than a sketch or mockup, is a key strength of procedural material design software. The digital material lends a level of concreteness to the first prototype, an abstract definition of a sensory experience, and serves as a visual and strategic reference for creating the next prototype, a physical sample.

A material in our collection named "tensile gelatinous membrane" demonstrated many of the qualities outlined above, leading us to select it as a candidate for this digital-first workflow. To design a material that felt biological yet otherworldly, filmy and effervescent yet robust, we started by setting parameters for roughness and color, creating a slick translucent effect. Air bubbles on the surface and (seemingly) embedded in the material were used to suggest its viscosity and thickness, and a webbed pattern with raised edges was added to the heightmap, suggesting that the base material might be tensioned or spanning across edges like a soap film. With this approach, solutions to open-ended or contradictory prompts are found in an intuitive, free-associative way, with the designer borrowing visual features from familiar materials to imbue the prototype with the same connotations and implied tactile qualities. We then used the digital material to inform the physical material: the design choices during the procedural design process, which could not have been made in a textile fabrication setting, empowered us to select unconventional raw materials and methods. The webbed scaffolding was digitally embroidered, with several layers of thread built up to create a piece of dimensional lace. Casting a liquid silicone into the spaces between lace segments created a thin, stretchy yet constrained film with the desired "tensile membrane" effect. There were practical advantages to this workflow, including the ability to generate fabrication inputs (eg. a digital embroidery file) directly from the digital material's node graph. More significantly, deferring decisions about materials and methods until after developing the material in an unconstrained, speculative and highly visual space can lead to "hybrid" (eg. embroidery-casting) or entirely new ways of making textiles.

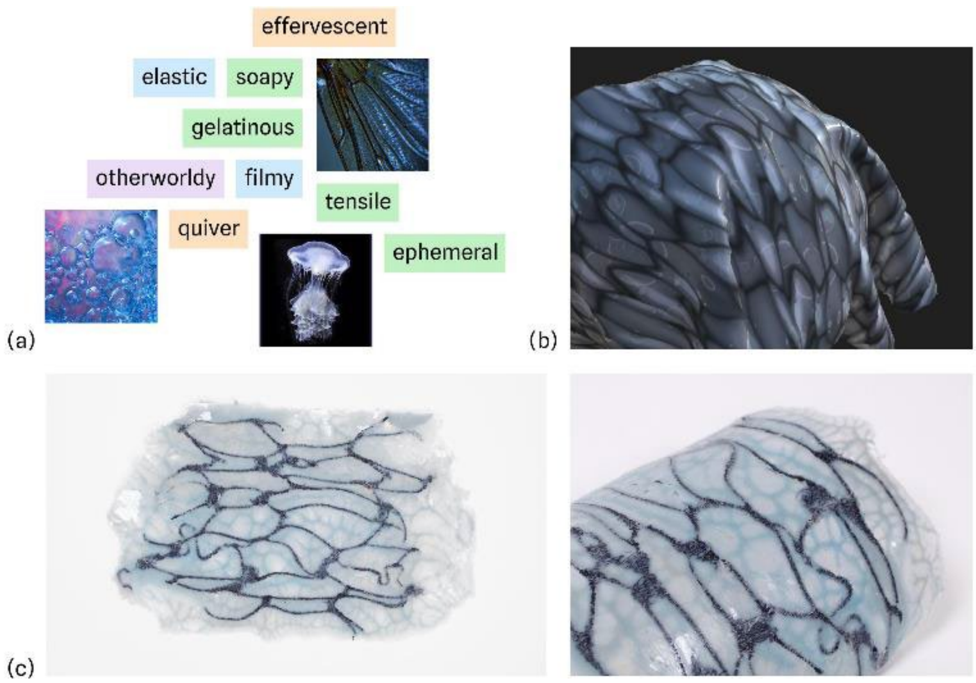


Figure 9: In this workflow, the generalized swatch (a) informs the digital prototype for "tensile gelatinous membrane" (b), followed by a physical interpretation (c).

Temporal qualities of material prototypes

The parametric nature of the swatch in our workflow aligns with the idea of the textile sampler, illustrating many potential states in which a material concept can be realized. With procedurally designed textiles, one way to visualize this solution space is to animate the material. We differentiated between two uses of movement in digital materials: simulating physical motion, as in a pleated textile that expands and contracts, and traversing a space of possibilities. While behaviors appear in the latter case that aren't physically plausible - the material transforms from one instance to another, seemingly flickering, pulsing or breathing - this mode of representation is valuable for understanding the boundaries of the generalized swatch and identifying convergences within it. For a digital textile with a complex surface pattern and pleated structure, based on qualities including "drifting", "whoosh" and "caress", we built a node graph that closely resembled the actual steps of designing a Jacquard-woven fabric. The textile's noise level (the degree to which yarn colors are randomly scattered), and the height and irregularity of its soft pleats, were exposed as parameters in the procedural design software so they could be quickly changed to update the material's appearance. Arranging the resulting variations into a temporal form allowed us to assess the many states that fit the "generalized swatch" definition, something a physical fabric doesn't permit. The underlying structure of this digital prototype also allowed us to extract parameters to fabricate any instance of the design that met the initial sensory criteria.

Figure 10: Stills from the animated material sample illustrate distinct intersections of noise, pleat height and irregularity.

Conclusion

By acknowledging the multiple representations inherent to a single material, we propose a unique form of prototyping that privileges experiential qualities. Our method replaces the traditional swatch in textile design with the "generalized swatch", which encloses a constellation of material representations and sensory qualities. This form of prototyping specifies experiential qualities at the beginning and derives a material design from them, an inversion of typical material-selection processes that enables designers to develop sensorially complex materials. Textile designers currently lack tools to envision the sensory or temporal aspects of materials in the design stage, despite the rich potential of textiles to operate in these dimensions. With rapid improvement of appearance-based modeling software, we see an opportunity to apply strategic design methods that consider the multisensory properties that appearance and movement can imply. We aim to demonstrate the value of these tools, and potential ways of reconfiguring them, in support of the ideation of novel textile materials.

Figure 11: Additional knit, woven and non-textile materials developed from generalized swatches.

Future steps for this work include organizing digital and physical textile samples into a library, in which users can compare and assess materials. Studying the range of responses allows us to measure, and subsequently tune, the variability in our design methods. Prior knowledge and cultural context play a large role in how we perceive materials, and are certainly present when we generate new materials from expected perceptual behaviors. Asking outside participants to describe their experiences of encountering our materials, which originated from sensory descriptions, closes the loop on our design process and indicates how it might be modified to produce more precise, powerful or favorable conditions of material interaction. We acknowledge that our current methods are limited by various factors: the examples in this paper were developed by English-speaking designers, so some language-specific details, like onomatopoeia and semantic ambiguity, will differ across linguistic contexts. Working primarily with text, as in the generalized swatch, may be challenging for designers accustomed to compiling visual and material references to inform their work. Moreover, our methods are not completely automatic or generative like text-to-image tools: they require the designer to both provide and synthesize inputs to create a novel material idea. While these steps necessitate a certain amount of creative effort, we find that they lead to highly unique and sensorially rich material outcomes.

We also see an opportunity to expand the format of our material prototypes by including audio or interactive movement behavior, further heightening the sense of materiality in settings where the tactile aspect is missing. There are well-established software pipelines for bringing digital materials into 3D modeling, gaming and VR environments, where they can change dynamically based on user inputs. In these systems, the underlying design of the procedural material (ie. the node graph itself) closely controls the types of responsive behaviors that can occur, so designers may choose to structure the digital material in a way that mimics the physical logic of an existing one. Properties like thickness, bending stiffness and elasticity can be directly applied, rather than visually implied, through the use of software plugins that enable PBR materials in CLO, a popular digital fashion-design program. A thorough investigation of these methods could give designers the ability to more fully prototype material experiences early in the design process.

Acknowledgments

The authors would like to thank VTRG Feeling Fabrics research assistants Zoë Pulley, Sadia Quddus, Alexandra Soiseth and Julie-Louise Zeitoun for being receptive to the open-endedness of this research and helping to define this body of work; as well as to Adobe 3D&Immersive-Substance members Alwyn Hunt, Tiffany Chang, Nicolas Paulhac and Adobe Research member Jerome Derel for joining as guest critics and their encouragement to forge ahead. We are grateful for insightful conversations with Kathy Wu and Holly McQuillan.

This research is generously funded by VTRG, RISD Textiles Department, Fine Arts Division and a Professional Development Fund Grant to Joy Ko.

References

Aktaş, B.M., & Groth, C. (2020). Studying Material Interactions to Facilitate a Sense of Being with the World. In Proceedings of DRS 2020 International Conference (4), 1659-1676.

Albers, A. (2017). On Weaving. Princeton: Princeton University Press. (Original work published 1965)

Ashby, M., & Johnson, K. (2002). Materials and Design: The Art and Science of Material Selection in Product Design. Oxford: Elsevier.

Atkinson, D., Orzechowski, P., Petreca, B., Bianchi-Berthouze, N., Watkins, P., Baurley, S., Padilla, S., & Chantler, M. (2013). Tactile Perceptions of Digital Textiles: A Design Research Approach. In CHI '13: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 1669-1678.

Barati, B., Karana, E., & Foole, M. (2017). 'Experience Prototyping' Smart Material Composites. In EKSIG 2017: Alive. Active. Adaptive. Proceedings of the International Conference on Experiential Knowledge and Emerging Materials, 50-65.

Buchenau, M., & Suri, J. F. (2000). Experience Prototyping. In DIS '00: Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques, 424-433.

Camere, S., & Karana, E. (2018). Experiential characterization of materials: Towards a toolkit. In Proceedings of DRS 2018 International Conference (4), 1685-1705.

Camere, S., Schifferstein, H. N. J., & Bordegoni, M. (2015). The Experience Map. A Tool to Support Experience-driven Multisensory Design. In Proceedings of the 9th Annual Conference on Design and Semantics of Form and Movement, 147-155.

Cary, L. (2013). Exploring a language of gestures and emotional responses to textiles. [Master's thesis]. University College London.

Douglas, A., & Gulari, M. N. Understanding experimentation as improvisation in arts research. Qualitative Research Journal, 15(4), 392-403.

Edelkoort, L. (2012, September 22). [Lecture video recording]. Dezeen Live. https://www.dezeen.com/2012/12/28/super-technology-is-going-to-ask-for-super-tactility-li-edelkoort-at-dezeen-live/.

Giaccardi, E., & Karana, E. (2015). Foundations of Materials Experience: An Approach for HCI. In CHI '15: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, 2447-2456.

Igoe, E. (2020). Where Surface Meets Depth: Virtuality in Textile and Material Design. In Y. Lee (ed.), Surface and Apparition: The Immateriality of Modern Surface (pp. 77-90). London; New York: Bloomsbury Visual Arts.

Klefeker, J., Striegl, L., & Devendorf, L. (2020). What HCI Can Learn from ASMR: Becoming Enchanted with the Mundane. In CHI '20: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1-12.

Laughlin, Z. (2010). Beyond the Swatch: How can the Science of Materials be Represented by the Materials Themselves in a Materials Library? [Doctoral dissertation]. University of London.

Miodownik, M. A. (2007). Towards designing new sensoaesthetic materials. Pure and Applied Chemistry, 79(10), 1635-1641.

Parisi, S., & Rognoli, V. (2017). Tinkering with Mycelium. A case study. In EKSIG 2017: Alive. Active. Adaptive. Proceedings of the International Conference on Experiential Knowledge and Emerging Materials, 66-78.

Parisi, S., Rognoli, V., & Ayala Garcia, C. (2016). Designing materials experiences through passing of time – Material driven design method applied to mycelium- based composites. In Celebration & Contemplation: Proceedings of the 10th International Conference on Design & Emotion (239-255).

Petreca, B. (2017). Giving Body to Digital Fashion Tools. In S. Broadhurst & S. Price (eds.), Digital Bodies: Creativity and Technology in the Arts and Humanities (pp. 191-204). London: Palgrave Macmillan.

Rognoli, V. (2010). A Broad Survey on Expressive-Sensorial Characterization of Materials for Design Education. METU Journal of the Faculty of Architecture, 27(2), 287-300.

Rognoli, V., & Ayala Garcia, C. (2018). Material activism. New hybrid scenarios between design and technology. Cuadernos Del Centro De Estudios De Diseño Y Comunicación, (70), 105-115.

Rognoli, V., & Parisi, S. (2020) Material Tinkering and Creativity. In L. Clèries, V. Rognoli, S. Solanki, & P. Llorach (eds.), Material Designers: Boosting talent toward circular economies (pp. 20-26). Elisava, Politecnico di Milano, Matter.

Talman, R. (2019). Designing for Multiple Expressions: Questioning Permanence as a Sign of Quality in Textiles. Journal of Textile Design Research and Practice, 6(2), 201-221.

Vallgårda, A., Winther, M., Mørch, N., & Vizer, E. E. (2015). Temporal Form in Interaction Design. International Journal of Design, 9(3), 1-15.

Veelaert, L., Du Bois, E., Moons, I., & Karana, E. (2020). Experiential characterization of materials in product design: A literature review. Materials and Design, 190, 108543.

Wilkes, S.E., & Miodownik, M.A. (2018). Materials library collections as tools for interdisciplinary research. Interdisciplinary Science Reviews, 43(1), 3-23.

Elizabeth Meiklejohn

Elizabeth Meiklejohn is a textile designer and researcher with a focus on the three-dimensional qualities and movement behaviors of fabrics. Her work blends procedural design, digital simulation and hands-on craft methods to achieve these complex forms and capabilities, all while investigating material origins and lifecycles. She recently completed her MFA in textile design at the Rhode Island School of Design, where she specialized in woven fabrics and was a member of the Virtual Textiles Research Group. Through ongoing research, Elizabeth explores techniques that enable fabrics to move, transform and respond to external forces. This practice is motivated by curiosity about these static objects' potential to interfere with sensory perception, through haptic and visual illusory effects. Simultaneously, she develops software tools, notation systems and methodologies that allow creative practitioners to design and fabricate materials with intricate or unconventional structures, seeking to create new visual languages for understanding textile forms.

Felicita Devlin

They are an interdisciplinary artist/designer from Fort Lauderdale, FL, currently residing in Providence, RI. Their research investigates and reflects upon their personal consumption of digital culture and technology. As technology further intermeshes the internet into the physical realm, it has produced its own materiality into our culture. They are primarily focused on how technology has been a portal/paradise for queer expression, as an extension of survival. As a way to celebrate the fluidity & formlessness of gender and identity through themes of sci-fi, horror, and the unknown.

Caroline Silverman

Caroline Silverman is an interdisciplinary artist who focuses on the intersection of object, narrative, and context. Working predominantly with textiles, her work explores how the soft things that people live with reflect the realities and records of their experiences. In the process of exploring what draws people to their objects, she has made quilts, writing, embroideries, tools, poetry, garments, books, and paintings to help her better understand this relationship. In her work she contemplates how these objects are often made with the intention to provide comfort and protection, and strives to extend these gestures to her collaborative work and teaching. Caroline's recent research has delved into the tactile and intimate relationship between textiles and the body, specifically looking at quilts and embroidery as an extension of memory and embodied experiences. She thinks this relationship is particularly important to consider in analog and digitalized ways. Caroline lives and works in New York City, and travels often to Providence where she teaches at the Rhode Island School of Design.

Joy Ko

Joy Ko is an artist and educator. Her teaching, research and writing explore the use of computation and digital technologies to augment and extend the creative process. In her studio, she renders walks in the woods, mixes memory with imagination, and keeps things moving forward by staying (more or less) still. Trained as a mathematician, she has found her way towards the intersection of mathematics, computation, art and design. She believes art and design has a unique role in guiding society: to anticipate changes, to explore these critically and to show many possible futures. Since 2010 she has taught at the Rhode Island School of Design (RISD) and contributed to multiple departments including Architecture, Textiles and Industrial Design. She helps lead the Virtual Textiles Research Group (VTRG).

Beyond Boundaries: 3D Printing and Functional Materials as Boundary Objects to Mediate Interdisciplinary Collaboration

Levi Swann, Queensland University of Technology, Australia
Heather McKinnon, Queensland University of Technology, Australia
Nathan R. B. Boase, Queensland University of Technology, Australia
Mehrnoosh Mirzaei, Queensland University of Technology, Australia
Sandra Wiedbrauk, Queensland University of Technology, Australia
Samantha Wigman, Queensland University of Technology, Australia

Abstract

This research presents an interdisciplinary collaboration between design and chemistry researchers, which aimed to design and fabricate ultraviolet sensor prototypes using functional, 3D printed colour change material. Design and chemistry research streams each employed specialised knowledge and processes: design to engage users and to develop 3D printable concept designs; chemistry to synthesise a colour change material that could be integrated with 3D printing and to evaluate material outcomes. Mediating this collaboration was 3D printing technology and prototypes. These acted as boundary objects, which provided a stable condition at the boundary of each discipline's expertise where information could be traded, and knowledge integrated. They facilitated syntactic and semantic understanding whereby a common language developed around the 3D printing process and outputs, as well as revealed differences and dependences of each discipline relating to what information was deemed meaningful and how it was used to progress respective contributions. The success of 3D printing as a boundary object was attributed to its effectiveness at mediating and embodying each stream's contributions. Chemistry knowledge was input into the 3D printing technology in the form of a colour change material integrated with photopolymer resin. Design knowledge generated through user engagement and synthesised in conceptual designs was input into the 3D printing technology in the form of 3D models. The knowledge of each stream became visible to the other through this process and in the 3D printed prototypes. This established common ground on which to evaluate and negotiate outcomes to ensure convergence on a mutually acceptable outcome. The research outcomes illustrate the potential for 3D printing technology and advanced prototypes to facilitate innovative outcomes in emerging research fields. This is important given the recognised challenges of interdisciplinary research and the value it holds for generating novel and productive outcomes when fostered effectively.

Interdisciplinary Research; 3D Printing; Design; Chemistry; Boundary Objects

The context of this paper is interdisciplinary research that uses 3D printing to support shared knowledge development and facilitate research innovation. Interdisciplinary collaborations are widely valued as they create opportunities to break new ground at the intersection of disciplinary expertise (Szostak et al., 2016). They are especially valued in academic contexts due to the potential for rich and innovative outputs that are often not possible using approaches siloed within the boundaries of a single discipline's knowledge (Dalton et al., 2017). 3D printing is a compelling technology for enabling interdisciplinary collaboration as its underlying technology, processes, inputs, and applications naturally traverse a variety of discipline knowledge. For example, in a case study exploring the design of 3D printed hearing aids, Heiss (2020) labels 3D printed prototypes as 'boundary objects' that enabled discipline-specific knowledge to be integrated and that facilitated collaboration from an interdisciplinary team. Similarly, 3D printed anatomic models for preoperative planning represent an intersection of expertise. They require CT scanning expertise, 3D modelling process knowledge to translate CT scans to printable files, and the 3D printing outcomes provide invaluable benefit to surgical knowledge and patient education (Green et al., 2016). Innovative processes like these do not sit within a single person's knowledge and expertise.

Like these examples, we similarly position 3D printed prototypes as boundary objects capable of mediating interdisciplinary collaboration. However, we also argue that facilitating collaboration is not limited to physical prototypes but is also influenced by the underlying 3D printing technology and processes. This is because our collaboration occurred between design and chemistry with the aim to design and fabricate ultraviolet (UV) sensor prototypes using functional, 3D printed colour change material. Creating 3D printed prototypes required synthesis of colour change material into the 3D printing technology and design process. An experimental dialogue was required, which took place through the 3D printing materials and technology.

We begin this paper by outlining the context of interdisciplinary collaborations and boundary objects. We then present a case study of our collaborative work designing and prototyping 3D printed UV sensors incorporating functional colour change material. From this case study, we draw conclusions about the capacity for 3D printing with advanced materials to support interdisciplinary collaborations and facilitate innovative research fields.

Background

Interdisciplinary collaborations are an effective way to produce innovative outcomes that are not otherwise possible by a single discipline's knowledge and expertise (Dalton et al., 2017; Szostak et al., 2016). Spanning multiple discipline boundaries to access the knowledge of several specialist domains enables knowledge to be recombined in creative ways (Hsu & Lim, 2014; Van de Ven & Zahra, 2017). This type of boundary spanning collaboration is a key characteristic of post-industrial work contexts (Bechky, 2006; Nicolini et al., 2012). It is an imperative in academic contexts due to the increasing complexity of problems being faced and opportunities for new research fields (Arnold et al., 2021). Accordingly, many universities encourage collaboration across disciplines through organisational structure and incentives (Arnold et al., 2021; Leahey & Barringer, 2020). Despite their recognised value, enabling collaborations that span disciplines, departments, organisations, and industries, is challenging. To create truly innovative outcomes and enable effective knowledge integration requires overcoming the boundaries of disciplinary specialisation while also amplifying specialised knowledge in ways that are comprehensible to a community of varied individuals (Caccamo et al., 2022).

A longstanding concept used to help achieve knowledge integration is that of boundary objects. Star and Griesemer (1989) explain boundary objects as being central for translating viewpoints of actors whose knowledge and expertise is heterogeneous, and therefore do not have adequate models for understanding each other's work. Initially reported in scientific contexts, research on boundary objects has since spanned many disciplines (Caccamo et al., 2022). It is understandable then that boundary objects can constitute a range of artifacts (Star & Griesemer, 1989). However, as a general characteristic, their success can be determined by the extent to which they are mutually understood in practice and sufficiently create common ground to mediate collaboration (Bechky, 2003; Carlile, 2002; Levina & Vaast, 2005). For new product development, examples of boundary objects include repositories (e.g., databases, libraries), forms and methods (e.g., standard methods of enquiry and reporting), and objects or models (e.g., sketches, prototypes, drawings) (Carlile, 2002).

Boundary objects can be thought of as a bridge between worlds. That is, they open channels for collaboration but do not necessarily create deep understanding. In fact, sharing and understanding can be incomplete or partial. Their real strength lies in creating conditions for collaboration through their interpretive flexibility (Nicolini et al., 2012). Flexibility is important as deep expertise within a discipline should be maintained, alongside the ability to engage with knowledge of other disciplines (Brown et al., 2015; Conley et al., 2017). As a relevant example, Heiss (2020) explained how 3D printed hearing aid prototypes acted as boundary objects that mediated information trading and reduced conflict amongst a signal processing expert, a mechanical engineer, an audiologist, an electrical engineer, and a designer. Each actor's knowledge was transformed through parallel, proactive, and individual contributions to the design of a hearing aid and could be progressed with a shared understanding. Likewise, 3D models have been used as a persuasive tool between designers, project managers, and other stakeholders to achieve better results during the product development stage in a footwear company (Lauff, 2018). Prototypes played a communicative role and facilitated social interaction between stakeholders. They embodied technical knowledge and meanings that different types of stakeholders could translate, decode, and re-encode.

The collaborative work at the centre of this paper is between design and chemistry. Each of these disciplines can be thought of as having their own worlds, comprising specific knowledge, methods, approaches, and beliefs. Having boundary objects to bridge these worlds is therefore of value. As a scientific discipline, chemistry includes characteristic activities of "systematic observation and experimentation, inductive and deductive reasoning, and the formation and testing of hypotheses and theories" (Hepburn & Andersen, 2021). Although knowledge and perspectives do vary (Hepburn & Andersen, 2021; Sankey, 2013), the scientific method applied represents a systematic and repeatable approach that relies on traits of precision, validation, specificity, and traceability, among others. Chemistry, like many of the natural and physical sciences, prefers quantitative evaluation of hypotheses through reproducible experimentation as the means to establish consensus (Murray, 1999).

The analogue to the scientific method for design, the design process, is by comparison 'fuzzier'. Design is principally concerned with changing existing states into preferred ones (Simon, 1970). For these purposes, abductive reasoning is used, which has been described as "a logical way of considering inference or best guess leaps" (Kolko, 2010, p. 20). Kolko explained that abduction is applied within the confines of a design problem where a range of information, including personal experience, problem constraints, observations, and actions, is brought together to generate new knowledge. This knowledge generation is facilitated by an iterative design process in which sketching, making, testing, and evaluating, result in design concepts that are then reinserted back into the design process. Typically, both the problems and solutions become clearer over the course of this process until a solution is generated (Cross, 1982; Kolko, 2010; Lawson, 2005; Smithers, 2002). It is also common for designers to foster interaction and collaboration among individuals from diverse disciplines during the design process because it generates many vantage points from which to tackle a problem (Tharchen et al., 2020; Välk et al., 2019). A well-recognised representation of the design process is the Double Diamond, which depicts a divergent and convergent thinking process moving through phases of discovery and defining of challenges, and then developing and delivering a solution. It is normal for phases to be moved between in a non-linear way, sometimes returning to the beginning if needed (Design Council, 2019).

Despite any differences that may be present, it is ultimately in the best interest of collaborating disciplines to produce new knowledge that acts as a catalyst for innovation. Effective collaboration has the potential to combine knowledge for these purposes. The following case study presents collaborative work between chemistry and design disciplines, which produced wearable UV sensors using functional, 3D printed colour change material. The role of 3D printing and resulting prototypes as boundary objects exemplify how such technology and outcomes support effective research collaborations and innovative research outcomes.

Case Study

This case study presents a collaborative interdisciplinary research project that aimed to design, synthesise, and fabricate a collection of wearable UV sensors using functional, 3D printed colour change material. Although many wearable UV sensors are commercially available, ranging from photochromatic to photoelectric, they have had inconsistent results on improving sun safe behaviours (Hacker et al., 2019; Robinson et al., 2020). Potential reasons for the low efficacy of these devices are numerous, and include aesthetics, interaction experience (Jarusriboonchai & Häkkilä, 2019; Wentzel et al., 2016), customisation, comfort (Miner et al., 2001; Pateman et al., 2018), maintenance, and how easily the devices fit into a user's daily routine (Lazar et al., 2015). This project sought to address many of these areas by designing a collection of aesthetic and function focused wearables that could seamlessly fit into a range of daily scenarios.

The project was supported by a Queensland University of Technology Early Career Researcher Scheme Grant, which actively encouraged interdisciplinary collaboration for team submissions. Our project collaboration occurred between design and chemistry researchers, with expertise from each stream contributing to specific aspects of the project (Figure 1).

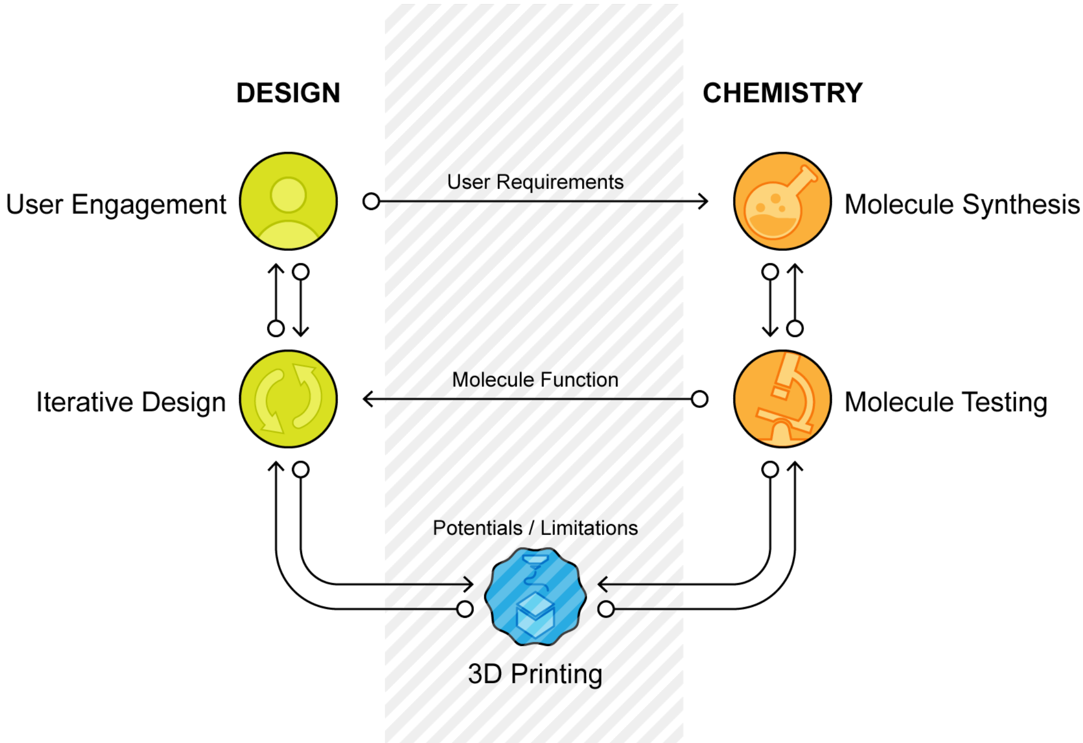


Figure 1: Project process showing design and chemistry stream interactions.

The design stream (Swann, McKinnon, Mirzaei, Wigman) included industrial design, interaction design and digital fabrication expertise. This stream engaged with young Australians (aged 18-30) to understand their outdoor activities, sun protection behaviours, and perspectives toward sun safety technologies. This process identified that young Australians engage in a wide range of activity types and adopt variable behaviours to sun safety. They recognise the importance of sun safe behaviour, however, admit that it is not always possible. Despite the availability of a wide range of wearable UV sensors (Huang & Chalmers, 2021; Zou et al., 2020) it was determined that low maintenance devices that do not require power yet are effective for cumulative measurement and discrimination between UV-A and UV-B, and provide real-time information are likely to succeed as wearable devices (Zou et al., 2018). Insights from user engagement and the literature informed the iterative design development of wearable UV sensors incorporating colour change material.

The chemistry stream (Boase, Wiedbrauk) included synthetic organic and polymer chemistry expertise. This stream focused on the molecular design of a UV reactive colour changing molecule, known as a photoswitch, that could provide a robust, sensitive, and reusable material for use in UV responsive wearable sensors. A review of the literature identified a specific class of molecules, commonly referred to as diarylethenes, as possessing the required chemical properties that would meet the needs identified by the design stream (Irie et al., 2014). Molecular synthesis and characterisation were first used to validate the properties of these molecules in the context of the demands for UV sun safety. Synthesised materials were formulated into 3D printing resins and material evaluation determined the suitability of these materials as UV sensor devices.

The design and chemistry streams interacted throughout the project (Figure 1). Initially, user engagement let to the identification of user requirements, which informed desired functional characteristics of the molecule. For example, duration over which colour change should occur to ensure suitability for different activity types. The molecule synthesis and testing outcomes provided knowledge of the molecule functionality, which provided constraints for iterative design. Central to the interactivity of the two streams was 3D printing. 3D printing acted as a common platform for each stream to communicate through and functional prototypes embodied the progress and outcomes of both streams simultaneously. The next section presents the activities of the chemistry stream, which is then followed by the activities of the design stream. The discussion details how 3D printing facilitated breaking the knowledge barrier by creating a shared language that simultaneously demonstrated the potentials and limitations of each stream's work. This allowed each stream to adjust their approach to ensure effective collaboration and that project aspirations were met.

Chemistry Stream: Molecule Synthesis and Evaluation

A UV sensor material was developed using diphenyl diarylethene photoswitches, with the following requirements: (i) absorbance in UV-A and UV-B region (300 – 400 nm), (ii) reversible isomerisation in the solid state, (iii) visually obvious colour change during irradiation, and (iv) resistance to fatigue over repeated use (Irie et al., 2014; Wiedbrauk et al., 2023). Photoswitches are a class of photochromatic material that can exhibit obvious colour change under UV light irradiation. The change is cumulative in that it doesn't spontaneously change back to the initial state colour when taken out of UV light. Instead, the material can be reverted to the original state when exposed to light of a different colour. In our case, the photoswitch changed from colourless to pink when exposed to UV light. Exposure to green light was used to switch it back to colourless. Our process, using a Green LED light box that we designed and fabricated, is shown in Figure 2. Cumulative measurement of UV exposure and reversibility of this nature makes the material ideal for use as wearable UV sensors. The material can be used to measure UV dose over the course of a day. It can then be reset, which makes it reusable over many instances of activity.

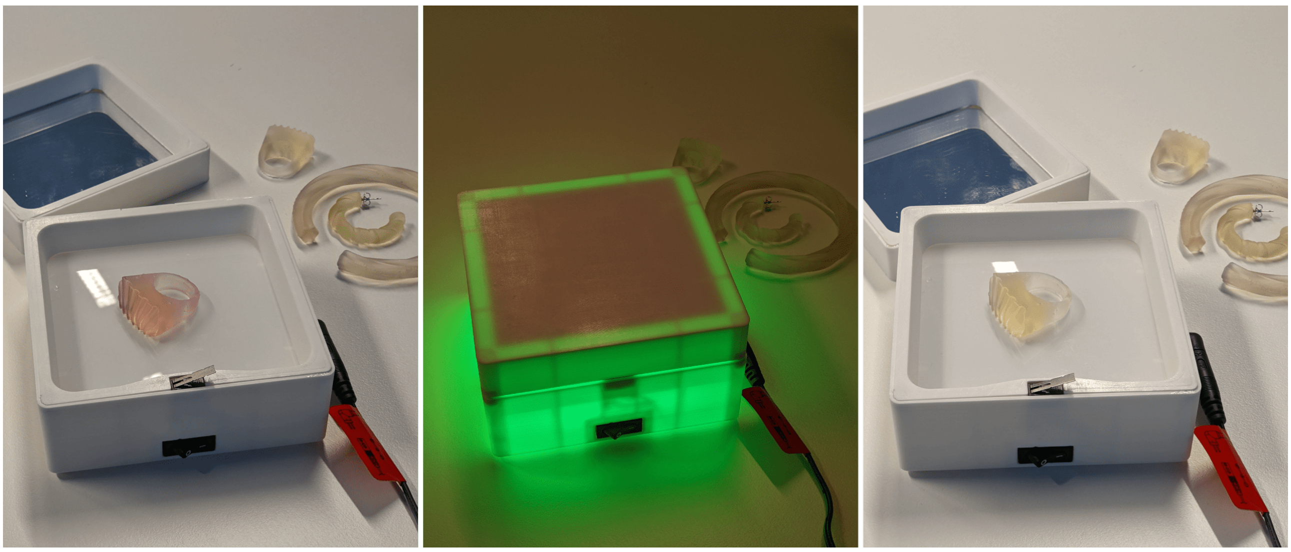


Figure 2: UV irradiated object exhibiting noticeable pink colour change (left), irradiated object inside LED light box under exposure to green LED light (middle), object changed back to colourless state following green light exposure (right).

A diphenyl diarylethene photoswitch was synthesised, from commercially available precursors in four steps, to provide a clear crystalline solid. It was ground into a fine powder using a mortar and pestle to allow for simple integration with fabrication methods. At first, the photoswitching properties were evaluated in solution to test that diphenyl diarylethene can act as a UV sensor at UV-A and UV-B doses relevant for sun protection. Following validation, the material was incorporated into silicone and then photopolymer resin for use in stereolithographic (SLA) 3D printing. The following sub-sections provide an overview of these processes.

Silicone Sensors

Silicone was selected as the first material to explore solid UV sensors using the diarylethene material due to low cost, ease of accessibility, high optical transmittance, and simplicity of process for creating basic 3-dimensional objects. Ground diarylethene photoswitch powder was incorporated into the resin component of a silicone kit, prior to mixing the catalyst component and curing the resin (final concentration 0.3 wt%). Simple flat shapes were produced to evaluate colour change and reversal. Figure 3 shows the material after irradiation with 6x 300nm UV bulbs at varying time intervals, and then the result of reversing the colour change following exposure to 10x Green LED bulbs for 2-hours.

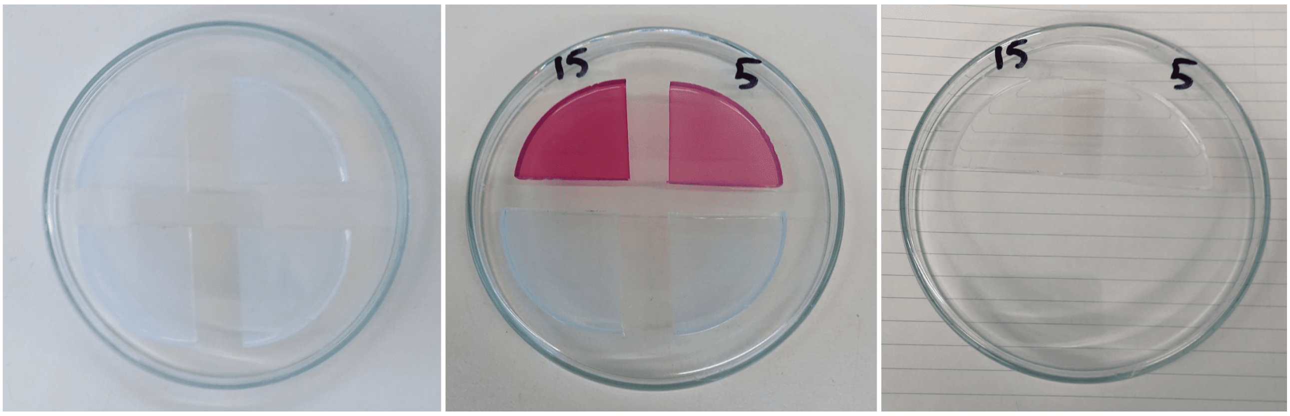


Figure 3: Cast silicone disks with unreacted and colourless diphenyl diarylethene (left), silicone disks showing colour change after exposure to 6x 300nm UV bulbs for 5 and 15 seconds (middle), silicone disks showing colour reversal after exposure to green light for 2-hours (right).

The samples in Figure 3 were provided to the design stream to indicate the colour change and appearance potential of the sensors. This visual understanding of the sensors informed concept design directions. These initial tests were also expanded on by the chemistry stream. To test sensitivity to harmful UV spectrum, the sensors were irradiated with UV-B light (25 $W.m^{-2}$) in a photoreactor at varying time intervals (0, 15, 30, 60, 120 seconds). Photographic analysis was used to quantify the colour response. Reversal tests were also conducted using a single low-powered green LED (1W, 520 nm) at varying time intervals with full discolouration achieved up to 2-hours (see Wiedbrauk et al., 2023).

Stereolithograpic 3D Printed Sensors

Following successful testing of the diphenyl diarylethene photoswitch material in silicone, the next phase was to explore its application to photopolymer resin for SLA 3D printing. This 3D printing technology was identified as an ideal candidate due to the potential compatibility of diphenyl diarylethene with the photopolymer materials used for SLA 3D printing. Specifically, photopolymer resin is a liquid which turns to a solid under exposure to UV-blue light during the stereolithography process. It was expected that ground diphenyl diarylethene could be successfully mixed with the photopolymer in its liquid state.

The first 3D printed tests were produced using an Elegoo Mars 2 Pro SLA 3D printer. NOVA3D high transparency photopolymer resin for 405nm SLA 3D printers was prepared with ground diphenyl diarylethene (0.3 wt%). A 3D file in the shape of a teardrop, created in Autodesk Fusion 360, was used for the test print. The shape was selected to explore whether material thickness affected the colour change intensity following UV exposure. Figure 4 shows the result of the test print, with one object irradiated with UV light from the sun and the other without UV exposure. The 3D printed object experienced visible warping of shape and one failed print, in which the teardrop shape was incomplete. This outcome was determined to be caused by the 3D print layer exposure settings' incompatibility with the NOVA3D high transparency photopolymer resin, rather than due to the inclusion of diphenyl diarylethene.

Figure 4: Initial test 3D print using diphenyl diarylethene (0.3 wt%) mixed with NOVA3D high transparency photopolymer resin printed on an Elegoo Mars 2 Pro SLA 3D printer.

To address the issue of warping and print failure, successive tests were performed using ground diphenyl diarylethene (0.3 wt%) mixed with NOVA3D clear resin for 405nm SLA 3D printers. Unlike the high transparency resin used previously, default settings for printing with the clear resin type with the Elegoo Mars 2 Pro were available. A series of test prints, using designs produced by the design stream, are shown in Figure 5. The first batch of prints were cured post-print using an Elegoo Mercury curing machine. Noticeable discolouration was observed; at first some yellowing of the print prior to exposure, and then following UV exposure the colour change presented as orange, instead of the desired pink. To explore the cause of the discolouration, a subsequent batch of prints were not cured. It was hypothesised that the discolouration was caused either by excessive exposure to UV light from the full layer exposure approach used by the Elegoo Mars 2 Pro 3D printer or due to the pigmentation of the NOVA3D clear resin.

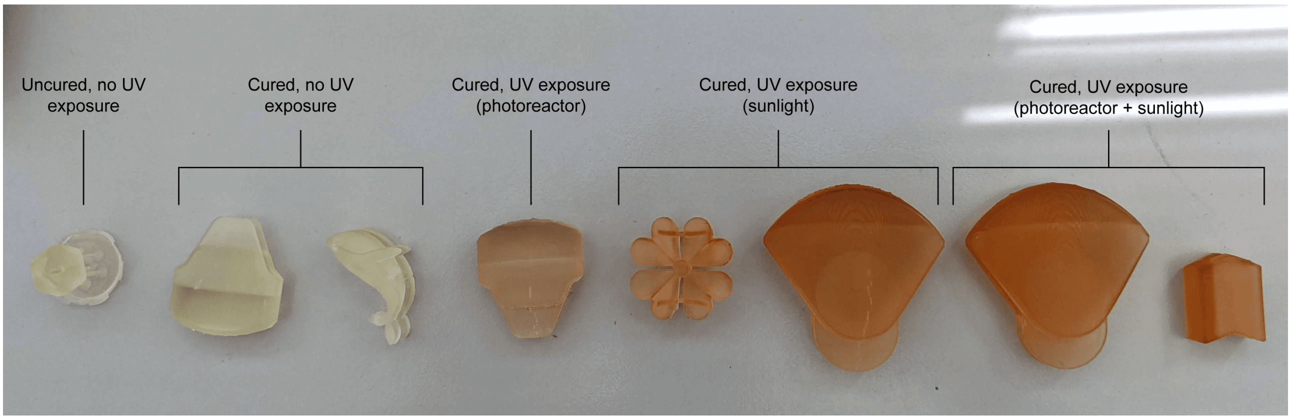


Figure 5: Test prints using NOVA3D clear resin for 405nm SLA 3D printers, showing prints cured and uncured post print, and unexposed and exposed to UV light in a photoreactor and/or sunlight.

Aiming to eliminate discolouration of the colour change, further 3D prints were tested using a Formlabs Form 2 SLA 3D printer with Formlabs Clear V4 photopolymer resin. This printer was chosen as it uses a focused laser to expose only a small portion of the resin on each print layer to UV at a time, opposed to whole layer exposure, as is the case with the Elegoo Mars 2 Pro. Additionally, Formlabs Clear V4 resin exhibits minimal pigmentation. The resin was prepared with the ground diphenyl diarylethene (0.3 wt%) and was stirred and sonicated for 2-hours to ensure complete dispersal. All 3D prints were produced with a layer resolution of 50 microns and automatically generated support layout using PreForm software. Completed prints were not artificially cured post-print. Instead, they were irradiated with UV light from the sun. Figure 6 shows the initial prints comparing some exposed to UV light and others unexposed. Comparing these prints to those produced using the Elegoo Mars 2 Pro and clear resin (Figure 5), distinct colour change with no discolouration is evident.

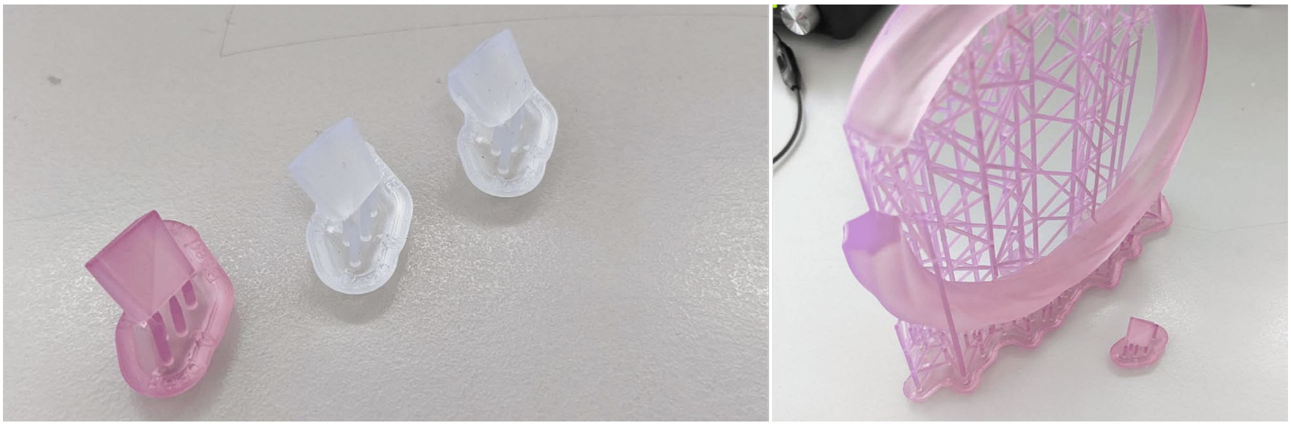


Figure 6: Comparison of UV light exposed print to unexposed prints produced using a Formlabs Form 2 SLA 3D printer with Formlabs clear V4 resin (left), larger print exposed to UV light produced using a Formlabs Form 2 SLA 3D printer with Formlabs clear V4 resin (right).

Having identified a 3D printer, resin, and diphenyl diarylethene combination capable of producing UV sensors with noticeable colour change, tests were then conducted to analyse dose response and stability over multiple cycles. A set of small beads (like those in Figure 6) were exposed to UV-B light and reset using 4x1W green LED lights over 10 cycles. Photographic analysis showed that the beads performed consistently regarding colourimetric response to UV and returning to the colourless state over several reset cycles (see Wiedbrauk et al., 2023).

Design Stream: Iterative Concept Design

Engaging with the young Australian (aged 18-30) user group during a series of design workshops led to identifying a range of activity types and associated sun protection strategies. From this, three design directions were specified, relating to routine (e.g., commuting to work), leisure (e.g., going to the beach, festivals), and recreation (e.g., playing sports, hiking) activities. An Iterative design development process, employing sketching and computer-aided design, addressed each direction and resulted in a range of design concepts (Figure 7). Concepts spanned various forms, typically relating to product categories of commonly worn jewellery and accessories including, bracelets, rings, earrings, straps, beads, and pendants.

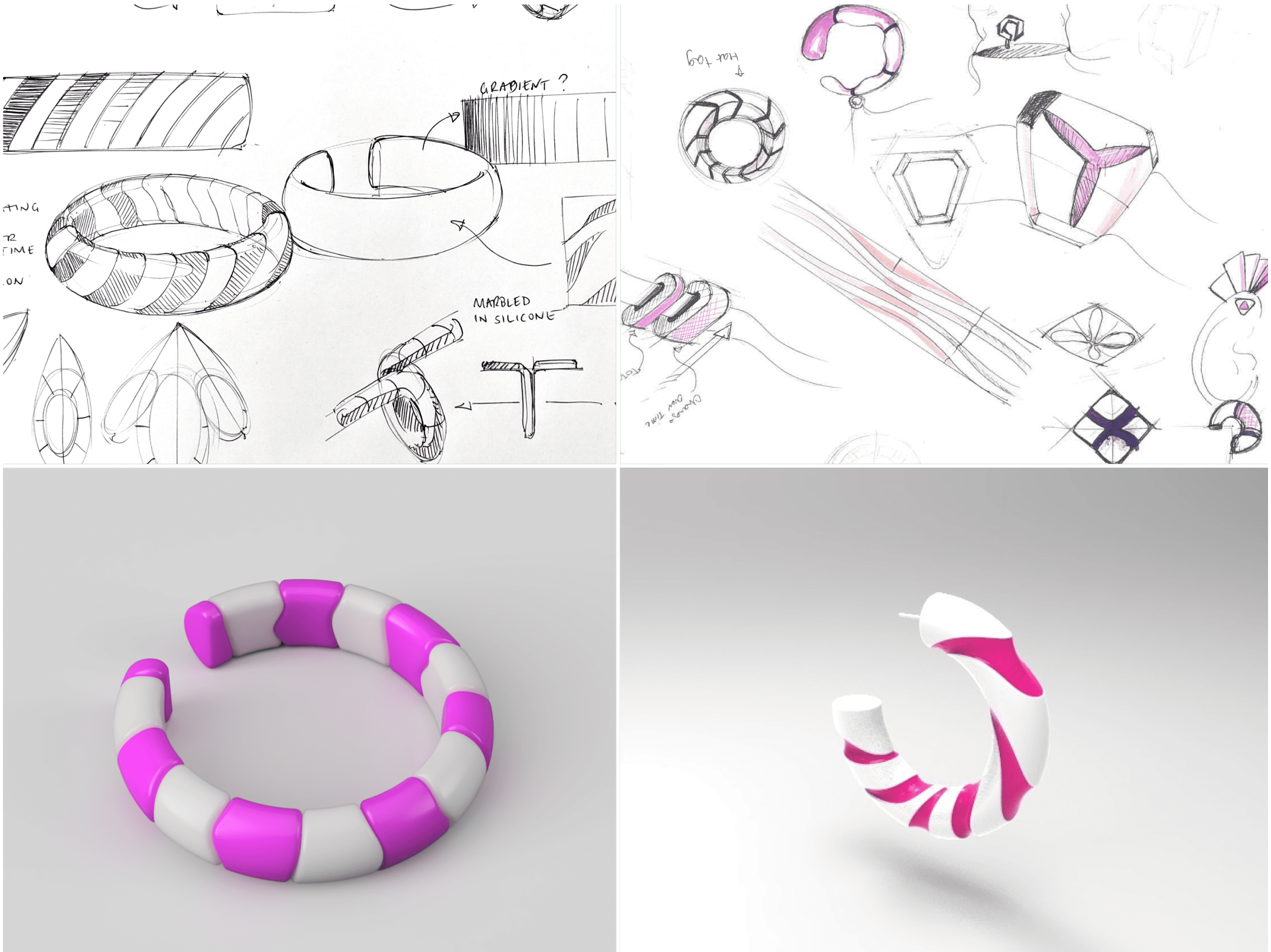


Figure 7: Sketches and computer-aided design renders exploring various design concepts.

At this early stage, concepts were generated without knowing the eventual material properties or that 3D printing would be used as the fabrication method. Therefore, design concepts focused on exploring aesthetics and aspirational functional requirements, such as customisable colour change over various durations (10-minutes – 2-hours), for a range of materials and fabrication approaches. As material synthesis progressed, the knowledge passed on from solution and silicone testing (refer to Figure 3) provided additional constraints that were incorporated into the designs. For example, representations of colour change were based on high levels of saturation observable in silicone tests. Likewise, rapid UV response times in which colour change occurred quickly led to designs that could be interacted with in novel ways to create functionality. For example, the ability to rotate parts of a design to expose the colour change material to UV only when a wearer wanted to.

Successful photopolymer tests using 3D printing (refer to Figure 4) established additional constraints. Now knowing that SLA 3D printing would be used for fabrication, designs comprising single body forms or limited parts were favoured. Concept designs unsuitable for SLA 3D printing, such as those in which the colour change material was integrated with textile or flexible material were abandoned. A finding of the first batch of 3D printed designs was that although the colour change was noticeable, it was less than expected based on the previous silicone tests (refer to Figure 6 and Figure 3). This prompted exploration of how design changes could be implemented to exemplify colour contrast. One strategy used was to adopt a two-tone design in which the colour change material was positioned next to a light colour material to create higher contrast (Figure 8).

Figure 8: 3D printed prototype adopting a two-tone design to enhance contrast of colour change.

Another strategy to enhance colour noticeability, was through the design of the objects' surfaces. It was observed that colour intensity was enhanced on sections of designs characterised by surface variation (i.e., rippled, textured, etc.) when compared to those with uniform (i.e., flat, smooth, etc.) surfaces. Thin wall sections and edges showed the highest colour intensity (Figure 9). This prompted the creation of more designs with variable surface textures and patterning to exemplify the colour change.

Figure 9: Noticeable increase in colour intensity on object edges and variable surface textures and patterns (left), designs were created with variable surface texture and patterns to highlight colour change (right).

The design stream's final output was a collection of designs spanning five categories (rings, necklaces, clips, bracelets, and earrings). Multiple prints of each design were produced to enable further quantitative analysis by the chemistry stream and qualitative analysis through a user study conducted by the design stream. It is our aim to develop the designs into commercially available products. The outcomes of these next stages will inform the project's future direction, including aesthetic and functional refinements, and materials and fabrication techniques suitable for producing larger quantities.

Discussion: 3D Printing as Boundary Object

This research has presented collaborative work between design and chemistry researchers that aimed to design and fabricate UV sensor prototypes using functional, 3D printed colour change material. A feature of this work was that 3D printing technology and the resulting prototypes served as boundary objects that mediated collaboration. We argue that 3D printing was an effective mediator because the knowledge, processes and methods of each stream were required to pass through and become embedded in the technology at multiple levels (Carlile, 2004). For design, this was the knowledge generated from user engagement, concept design, and computer-aided design. For chemistry, this was the knowledge generated through molecular synthesis, material fabrication and evaluation. This knowledge, and the related processes and methods, became visible to the opposing stream as a result of using the 3D printing technology and creating the prototypes. In this way, the 3D printing technology facilitated both syntactic and semantic understanding, which are two characteristics of successful boundary objects that facilitate joint problem solving (Carlile, 2002). The following discussion details these experiences.

3D printing and the resulting prototypes outlined in the case study operated as a mediator of dialogue that occurred between streams. The project inputs being progressed by each stream (i.e., design concepts and material synthesis) were effectively translated into physical prototypes that could be commonly understood. This outcome is described in the syntactical approach to boundaries, where boundary objects facilitate a shared language or syntax (Carlile, 2002). A similar characteristic was documented by Heiss (2020) in which diagrams of 3D models provided a visual language that could be comprehended by each actor in the product development process. In our case, 3D printing technology effectively mediated a shared language because it established a stable condition comprising a set range of parameters that the outputs of each stream had to adapt to and meet (Carlile, 2002). For the design stream, design knowledge from user engagement and concept design was embodied in the digital 3D model print files. For the chemistry stream, chemistry knowledge was embodied in the mixture of the diarylethene photoswitch and photopolymer resin. Each of these then became inputs for 3D printing that were mediated by the technology.

The resulting 3D printed prototypes combined the knowledge from the two streams in a way that could be mutually understood. The visible 3D printing process and prototypes allowed for the tacit specialist knowledge underlying information synthesis and the applied procedures to be made explicit (Carlile, 2004; Van de Ven & Zahra, 2017). Despite each respective stream not having a deep understanding of the other, this effective combining of knowledge created a way of discussing inputs that focused on the technology or prototype and not the technical and discipline specific knowledge that enabled it. An example of this from the case study was the dialogue that took place upon noticing that 3D prints exhibited discolouration. The chemistry stream hypothesised that the molecule may have decayed because of extended UV exposure, which led to adjusting the post-print process to shorter curing times or no curing time, and eventually adopting a different 3D printing technology. In this case, the language for discussing the issue did not focus on the material chemistry, but rather the 3D printing process. It was a practice-oriented vocabulary that existed on common ground (Levina & Vaast, 2005; Van de Ven & Zahra, 2017) and was understood by both streams as they were involved with and familiar with the 3D printing process. It was ultimately effective for facilitating evaluation and further iteration.

In addition to exchanging information, boundary objects enable learning about individuals' differences and dependences (Carlile, 2002, 2004). This relates to the semantic approach, which recognises that "even if a common syntax or language is present, interpretations are often different which make communication and collaboration difficult" (Carlile, 2002, p. 444). In the case study, differences emerged in what aspects of the prototypes were deemed meaningful, and how this information was used. For example, when the representational mode (Caccamo et al., 2022) of the prototypes changed from silicone to 3D printed photopolymer, observations that the 3D printed prototypes showed lower colour intensity prompted two different perspectives and approaches. The chemistry stream proceeded to analyse the colour response through a structured photographic evaluation to provide quantifiable results. In contrast, the design stream proceeded with shape revisions that incorporated greater surface variation, which upon visual inspection was determined to amplify the colour response (refer to Figure 9). These different responses revealed the knowledge and processes that each respective stream had to better understand and overcome the issue.

Observing differences at the boundary where 3D printing was positioned facilitated a trading zone for information exchange. Although the 3D printers and prototypes typically served as the focus of encounters, they often facilitated a much broader understanding and appreciation of the processes behind each stream's inputs. They created 'anchor points' for understanding each disciplines way of working (Välk et al., 2019), and fostered cooperative creativity; the joint generation, combining and realising of ideas (Page & John, 2020). For example, the chemistry team made regular visits to the design fabrication studio to understand how design process and materials fed into the 3D printing process. Likewise, the design team visited the chemistry lab to better understand the processes to create and evaluate the materials. Such interactions created an effective space for negotiation and the revealing of dependence, which is "a condition where two entities must take each other into account if they are to meet their goals" (Litwak & Hylton, 1962 in Carlile, 2002). As more understanding formed about each area of expertise and their dependences, the views and efforts of each stream were aligned (Seidel & O'Mahony, 2014). Ultimately, convergence on a solution that best satisfied both perspectives occurred.

Conclusion

This paper has presented an innovative collaboration between chemistry and design researchers to design and fabricate wearable UV sensors using functional, colour change material. Although the specialised knowledge from each respective discipline was fundamental to the project, 3D printing acted as an input device, which simultaneously provided constraints by its very nature as a technology platform and mediated constraints that were generated by the respective streams' outputs. The evolving interaction that occurred through the technology created new knowledge in an understandable medium that each stream could process and incorporate into their practice to progress individual work (Caccamo et al., 2022). The research demonstrates the capability of 3D printing technology and advanced prototypes as boundary objects to support interdisciplinary collaboration. Although this case study focused on a design-chemistry collaboration, we expect that 3D printing can mediate diverse collaborations in conditions where each discipline's knowledge can be input through the 3D printer and output in a form that combines this knowledge. Effectively navigating this process creates opportunities for innovative outcomes in emerging research fields.

References

Arnold, A., Cafer, A., Green, J., Haines, S., Mann, G., & Rosenthal, M. (2021). "Perspective: Promoting and fostering multidisciplinary research in universities." *Research Policy*, *50*(9), 104334. https://doi.org/10.1016/j.respol.2021.104334

Bechky, B. A. (2003). Sharing meaning across occupational communities: The transformation of understanding on a production floor. *Organization Science*, *14*(3), 312–330. https://doi.org/10.1287/orsc.14.3.312.15162

Bechky, B. A. (2006). Talking about machines, thick description, and knowledge work. *Organization Studies*, *27*(12), 1757–1768. https://doi.org/10.1177/0170840606071894

Brown, R. R., Deletic, A., & Wong, T. H. F. (2015). Interdisciplinarity: How to catalyse collaboration. *Nature*, *525*(7569), Article 7569. https://doi.org/10.1038/525315a

Caccamo, M., Pittino, D., & Tell, F. (2022). Boundary objects, knowledge integration, and innovation management: A systematic review of the literature. *Technovation*, 102645. https://doi.org/10.1016/j.technovation.2022.102645

Carlile, P. R. (2002). A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organization Science*, *13*(4), 442–455. https://doi.org/10.1287/orsc.13.4.442.2953

Carlile, P. R. (2004). Transferring, translating, and transforming: An integrative framework for managing knowledge across boundaries. *Organization Science*, *15*(5), 555–568. https://doi.org/10.1287/orsc.1040.0094

Conley, S. N., Foley, R. W., Gorman, M. E., Denham, J., & Coleman, K. (2017). Acquisition of t-shaped expertise: An exploratory study. *Social Epistemology*, *31*(2), 165–183. https://doi.org/10.1080/02691728.2016.1249435

Cross, N. (1982). Designerly ways of knowing. *Design Studies*, *3*(4), 221–227. https://doi.org/10.1016/0142-694X(82)90040-0

Dalton, B., Simmons, T., & Triggs, T. (2017). Knowledge exchange through the design PhD. In L. Vaughan (Ed.), *Practice Based Design Research* (pp. 65–76). Bloomsbury Academic.

Design Council. (2019). *Framework for Innovation: Design Council's evolved Double Diamond*. https://www.designcouncil.org.uk/our-work/skills-learning/tools-frameworks/framework-for-innovation-design-councils-evolved-double-diamond/

Green, N., Glatt, V., Tetsworth, K., Wilson, L. J., & Grant, C. A. (2016). A practical guide to image processing in the creation of 3D models for orthopedics. *Techniques in Orthopaedics*, *31*(3), 153–163. https://doi.org/10.1097/BTO.0000000000000181

Hacker, E., Horsham, C., Ford, H., Hartel, G., Olsen, C. M., Pandeya, N., & Janda, M. (2019). UV detection stickers can assist people to reapply sunscreen. *Preventive Medicine*, *124*, 67–74. https://doi.org/10.1016/j.ypmed.2019.05.005

Heiss, L. (2020). Iterative prototypes as 'boundary objects': Facilitating interdisciplinary collaboration of a modular hearing aid. *The Design Journal*, *23*(6), 865–883. https://doi.org/10.1080/14606925.2020.1824412

Hepburn, B., & Andersen, H. (2021). Scientific Method. In E. N. Zalta (Ed.), *Stanford Encyclopedia of Philosophy* (Summer 2021). Metaphysics Research Lab, Stanford University. https://plato.stanford.edu/archives/sum2021/entries/scientific-method/

Hsu, D. H., & Lim, K. (2014). Knowledge brokering and organizational innovation: Founder imprinting effects. *Organization Science*, *25*(4), 1134–1153. https://doi.org/10.1287/orsc.2013.0863

Huang, X., & Chalmers, A. N. (2021). Review of wearable and portable sensors for monitoring personal solar UV exposure. *Annals of Biomedical Engineering*, *49*(3), 964–978. https://doi.org/10.1007/s10439-020-02710-x

Irie, M., Fukaminato, T., Matsuda, K., & Kobatake, S. (2014). Photochromism of diarylethene molecules and crystals: Memories, switches, and actuators. *Chemical Reviews*, *114*(24), 12174–12277. https://doi.org/10.1021/cr500249p

Jarusriboonchai, P., & Häkkilä, J. (2019). Customisable wearables: Exploring the design space of wearable technology. *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*, 1–9. https://doi.org/10.1145/3365610.3365635

Kolko, J. (2010). Abductive thinking and sensemaking: The drivers of design synthesis. *Design Issues*, *26*(1).

Lauff, C. A. (2018). *Prototyping in the Wild: The Role of Prototypes in Companies* [Ph.D., University of Colorado at Boulder]. https://search.proquest.com/docview/2048347774/abstract/6283DC1505314CA4PQ/1

Lawson, B. (2005). *How Designers Think: The Design Process Demystified* (4th ed.). Architectural Press.

Lazar, A., Koehler, C., Tanenbaum, T. J., & Nguyen, D. H. (2015). Why we use and abandon smart devices. *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 635–646. https://doi.org/10.1145/2750858.2804288

Leahey, E., & Barringer, S. N. (2020). Universities' commitment to interdisciplinary research: To what end? *Research Policy*, *49*(2), 103910. https://doi.org/10.1016/j.respol.2019.103910

Levina, N., & Vaast, E. (2005). The emergence of boundary spanning competence in practice: Implications for implementation and use of information systems. *MIS Quarterly*, *29*(2), 335–363. https://doi.org/10.2307/25148682

Miner, C. S., Chan, D. M., & Campbell, C. (2001). Digital jewelry: Wearable technology for everyday life. *CHI '01 Extended Abstracts on Human Factors in Computing Systems*, 45–46. https://doi.org/10.1145/634067.634098

Murray, R. W. (1999). The scientific method. *Analytical Chemistry*, *71*(5), 153A-153A. https://doi.org/10.1021/ac990210y

Nicolini, D., Mengis, J., & Swan, J. (2012). Understanding the role of objects in cross-disciplinary collaboration. *Organization Science*, *23*(3), 612–629. https://doi.org/10.1287/orsc.1110.0664

Page, R., & John, K. (2020). Design prototyping as a translational tool for medical device commercialization. *Journal of Design, Business & Society*, *6*(Design for Medicine and Healthcare), 215–232. https://doi.org/10.1386/dbs_00012_1

Pateman, M., Harrison, D., Marshall, P., & Cecchinato, M. E. (2018). The role of aesthetics and design: Wearables in situ. *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, 1–6. https://doi.org/10.1145/3170427.3188556

Robinson, J. K., Durst, D. A., Gray, E., & Kwasny, M. (2020). Protection-adjusted UV dose estimated for body areas: Daily self-reported sun protection modification of wearable UV sensor dose. *Photodermatology, Photoimmunology & Photomedicine*, *36*(5), 357–364. https://doi.org/10.1111/phpp.12557

Sankey, H. (2013). Scientific Method. In *The Routledge companion to philosophy of science* (pp. 312–322). Routledge.

Seidel, V. P., & O'Mahony, S. (2014). Managing the repertoire: Stories, metaphors, prototypes, and concept coherence in product innovation. *Organization Science*, *25*(3), 691–712. https://doi.org/10.1287/orsc.2013.0879

Simon, H. A. (1970). *The Sciences of the Artificial* (Third Edition). The MIT Press. https://mitpress.mit.edu/9780262691918/the-sciences-of-the-artificial/

Smithers, T. (2002). Synthesis in designing. In J. S. Gero (Ed.), *Artificial Intelligence in Design '02* (pp. 3–24). Springer Netherlands. https://doi.org/10.1007/978-94-017-0795-4_1

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, `translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science*, *19*(3), 387–420. https://doi.org/10.1177/030631289019003001

Szostak, R., Gnoli, C., & López-Huertas, M. (2016). The importance of interdisciplinary research and teaching. In R. Szostak, C. Gnoli, & M. López-Huertas (Eds.), *Interdisciplinary Knowledge Organization* (pp. 1–33). Springer International Publishing. https://doi.org/10.1007/978-3-319-30148-8_1

Tharchen, T., Garud, R., & Henn, R. L. (2020). Design as an interactive boundary object. *Journal of Organization Design*, *9*(1), 21. https://doi.org/10.1186/s41469-020-00085-w

Välk, S., Maudet, N., & Mougenot, C. (2019). *Exploring how boundary objects can support multidisciplinary design and science collaboration*. International Association of Societies of Design Research 2019: Design Revolutions, 2-5 September, 2019, Manchester School of Art, Manchester Metropolitan University. https://iasdr2019.org/uploads/files/Proceedings/op-f-1164-Val-S.pdf

Van de Ven, A., & Zahra, S. A. (2017). Boundary spanning, boundary objects, and innovation. In F. Tell, C. Berggren, A. Brusoni, & A. Van de Ven (Eds.), *Managing Knowledge Integration across Boundaries* (pp. 241–254). Oxford University Press.

Wentzel, J., Velleman, E., & van der Geest, T. (2016). Wearables for all: Development of guidelines to stimulate accessible wearable technology design. *Proceedings of the 13th International Web for All Conference*, 1–4. https://doi.org/10.1145/2899475.2899496

Wiedbrauk, S., McKinnon, H., Swann, L., & Boase, N. R. B. (2023). Diarylethene photoswitches and 3D printing to fabricate rewearable colorimetric UV sensors for sun protection. *Advanced Materials Technologies*, 2201918. https://doi.org/10.1002/admt.202201918

Zou, W., González, A., Jampaiah, D., Ramanathan, R., Taha, M., Walia, S., Sriram, S., Bhaskaran, M., Dominguez-Vera, J. M., & Bansal, V. (2018). Skin color-specific and spectrally-selective naked-eye dosimetry of UVA, B and C radiations. *Nature Communications*, *9*(1), Article 1. https://doi.org/10.1038/s41467-018-06273-3

Zou, W., Sastry, M., Gooding, J. J., Ramanathan, R., & Bansal, V. (2020). Recent advances and a roadmap to wearable UV sensor technologies. *Advanced Materials Technologies*, *5*(4), 1901036. https://doi.org/10.1002/admt.201901036

Levi Swann

Levi Swann (PhD) is a Senior Lecturer in Industrial Design at Queensland University of Technology (QUT), and he is the Emerging Technologies Program Leader at the QUT Design Lab. Levi's research explores the complex interactions that take place among humans, technology, and their environments. He applies design-led approaches to understand complex issues, develop innovative solutions, and outline strategies for preferable futures. Current focus areas are the design of health wearables using additive manufacturing, human factors and expertise development in complex systems, and emerging technology forecasting and scenario development across various industry sectors including aviation, agriculture, and business.

Heather McKinnon

Heather McKinnon (PhD) is a Lecturer in Interaction Design in the School of Design at the Queensland University of Technology. Heather is a designer-researcher with the QUT Design Lab and More-than Human Research Lab, whose work and interests lie at the cross section of sustainable interaction design, design for climate awareness, and speculative design.

Nathan R. B. Boase

Nathan R. B. Boase is a Senior Lecturer at the Queensland University of Technology and a member of the Centre for Materials Science. He completed his PhD at the University of Queensland in 2015, under the supervision of Prof. Kristofer Thurecht on hyperbranched polymer theranostics. In 2019 he was recognised internationally as a CAS Future Leader in chemistry for his teaching and

research activities. His current research explores controlled synthetic strategies to design materials that can respond to their environment. These materials are applied to solve significant challenges in healthcare, such as antibiotic coatings, sun protection, nanomedicine, and antiviral therapies.

Mehrnoosh Mirzaei

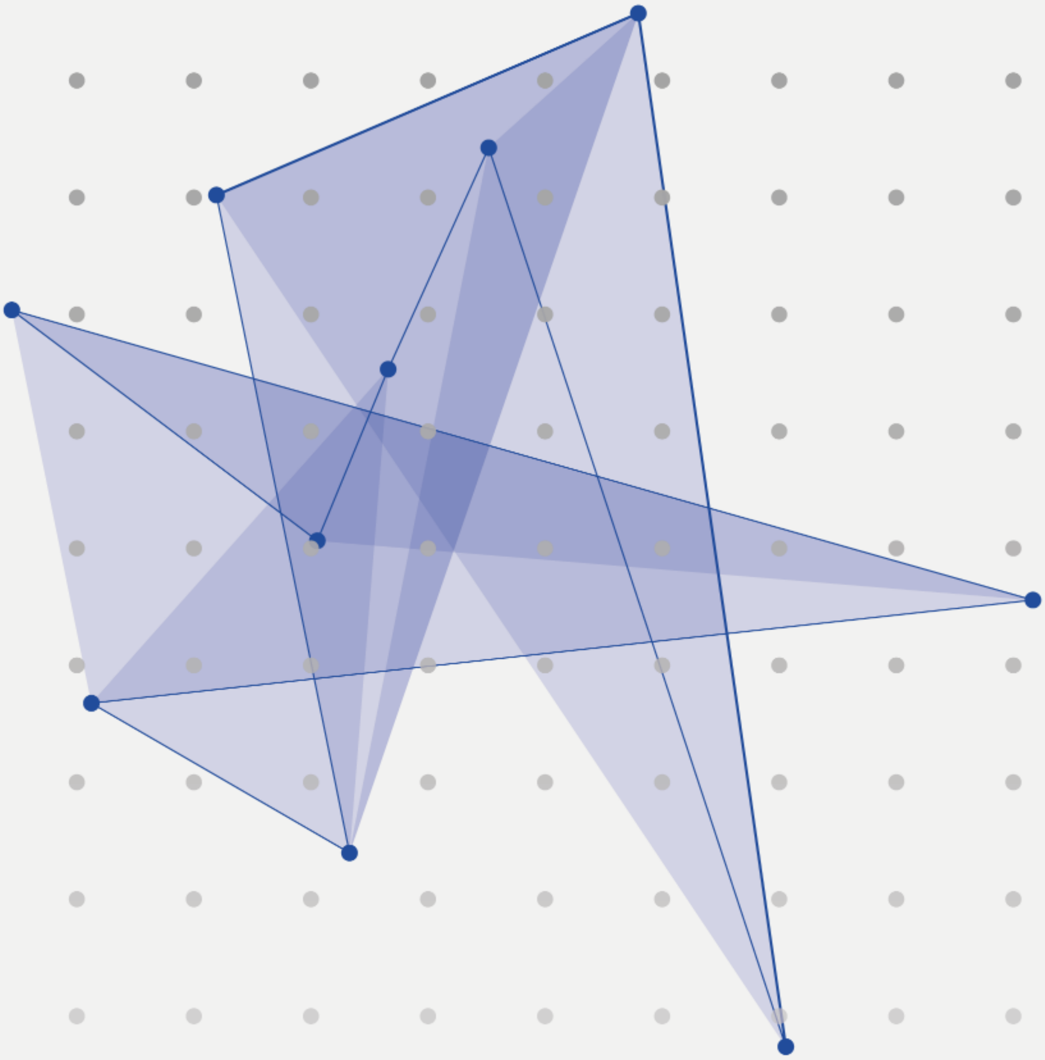
Mehrnoosh Mirzaei, a proficient industrial designer, recently completed her PhD in industrial design in the School of Design at the Queensland University of Technology. As a multidisciplinary designer and researcher, she is skilled in concept design, detail design, and computer-aided design. Mehrnoosh is focused on exploring and developing design-led initiatives to promote community capacity building and self-advocacy. Her current research centres on design-led initiatives in the fields of education, children learning and well-being. She is enthusiastic about using design-led initiatives and transdisciplinary research to examine the interaction between humans and technology. Through her design-led initiatives and transdisciplinary research, she aims to push the boundaries of the learning experience. In addition to working on various international design projects, she was awarded the A'Design award in the kitchenware category in 2017.

Sandra Wiedbrauk

Dr. Sandra Wiedbrauk is an organic chemist with a passion for photoswitches - molecules that can change their geometry when exposed to light. She studied chemistry at Ludwig-Maximilians-University in Munich, Germany, where she obtained her BSc and MSc. In 2013, she joined Prof. Henry Dube's research group to pursue her PhD in photochemistry. During this time, she investigated novel photoswitches and studied their properties in-depth. In 2018, she joined Queensland University of Technology in Brisbane, Australia, to apply her knowledge of photochemistry to advanced materials. Since 2022, she has been expanding her knowledge into medicinal chemistry, where she is exploring antimicrobial resistance.

Samantha Wigman

Samantha Wigman is a Digital Fabrication Technician at Queensland University of Technology, where she engages with designers in Research and Teaching & Learning in the Faculty of Creative Industries, Education and Social Justice. She has a background in Industrial Design and an interest in finding unique and practical applications for 3D printing and rapid prototyping throughout the design process. Sam works at the intersection of ideas and technology, and aims to advance our understanding and application of emerging technologies to tackle future global complex challenges.



Track 8: Education processes and methods

- To Prototype to Learn Fronting Uncertainties.
A Pedagogy Based on Anti-Disciplinarity, Thinkering and Speculation

- Prototypes, translation and research in social design education

- Prototyping of theories

- Role of Physical mock-ups in the Ideation phase: A thematic analysis of the Pedagogic approach

- From Prototype1.0 to Prototype3.0: Situated learning in Prototype design for Chinese labour education

To Prototype to Learn Fronting Uncertainties. A Pedagogy Based on Anti-Disciplinarity, Thinkering and Speculation

Francesco E. Guida, Department of Design, Politecnico di Milano

Abstract

This paper aims to present and discuss how teaching visual identity and experience design in Communication Design undergraduate education may be developed within an anti-disciplinary approach, adopting a speculative design framework. By adopting this approach, students become familiar with design as a problem-seeking and problem-finding practice, which encourages the development of concepts, scenarios, and results without any predetermined function. Moreover, they assume an open approach to final results and learn more about a design field intended as an *open context* with blurred borders.
The project's development is based on the principle of learning by doing, which consists of thinkering, making mistakes, repeatedly trying to improve the results, and acquiring competencies and skills. This method pushes the students to experiment with visual expressions and user experiences between two and three dimensions. They could range among many techniques and technologies, from analog to digital ones. Consequently, each design had to be theoretically discussed and physically verified by making prototypes. The prototyping phase has a double goal: on the one hand, to learn to use new tools, coding, and 3D printing environments; on the other, to test the results and effectiveness of design scenarios and concepts. By defining a design process and discussing the implications of an *anti-disciplinary approach*, the aim is to inquire how such framing may destabilize conservative methods and consolidate new practices into Communication Design learning.

Communication Design, Speculative Design, Thinkering, Design Education, Anti-Disciplinarity

Communication Design, usually intended as the area concerning the design of communicative artefacts and specifically of visual kind (Bucchetti, 2020, p. 117-118; Lussu, 2010), has nowadays expanded its boundaries, becoming more of an open context with blurred borders (Armstrong, 2009; Grimaldi, 2009). As affirmed by Grimaldi (2009, p. 28), "Blur is not a simple area in which the overlapping of themes determines an indistinct area. Blur is present everywhere, even in the dematerialization and deconstruction of traditional disciplines". By its very nature, Communication Design is a discipline situated among scientific knowledge, technical expertise, and art. Its knowledge and culture are becoming increasingly difficult to fit into any existing academic standard compared to the past. It is possible to define it as an anti-disciplinary field that requires a new set of values (Ito, 2016) in terms of knowledge, culture, and expertise because of the recent changes and advancements in technologies, expectations, and requests from users, audiences, and industry. In addition, it is possible to witness a clear switch from the centrality of function to the centrality of meaning (Antonelli, 2011a) and from the design of mere artefacts to systems, often adaptive and variable. These statements convey consistently the idea that Communication Design, far from being a mere problem-solving framework and a commercial-oriented practice, can also be a tool for exploration and questioning to investigate and front the uncertainty of our contemporaneity.

Some of the briefly introduced concepts constitute the background that inspired the teaching method and the assignments of a Final Synthesis Communication Design Studio (Bachelor in Communication Design, third year) over the last nine years. The students are prompted to work on visual and experience design related to thought-provoking themes, such as human conditions or emotions. The task is to design and prototype objects, installations, or interactive devices (defined as 'Communicative Machines' and at a 1:1 scale) in a critical and speculative framework, assuming the theme as an opportunity. The main goal is not necessarily to speculate on possible futures but to imagine a probable or plausible alternative present, taking real conditions and human superstructures (in the meaning of Harari, 2014) into account. This is the starting point to involve students in reflective practice (Schön, 1983) at various stages of the iterative design process, from scenario definition to concept, development, and prototyping. Consequently, Communication Design can be used as a tool and a means to validate speculation: the speculative process is correct when the design artefacts can effectively convey it. Design should not be considered a self-reflective practice but a powerful communication tool to promote speculation.

Students, divided into small teams, learn to cross disciplinary borders and adopt a critical approach to apparently fixed disciplines. The applied iterative process interprets experimentation as a means to find solutions, even in areas that teachers, professionals, or students do not master confidently (Triggs, 2003, pp. 7-17). For the prototyping phase (from first development to final steps), students adopt a 'learning by doing' approach, experiencing something close to the definition of "thinkering" (Antonelli, 2011b), for which a final result is obtained through progressive collective reworks. Berglund & Grimheden (2011, p. 737) confirm that both experimentation and prototyping consist of iterations of "trial and error", which is a significant feature in several aspects of a response development from design to final release.

Technological Fluency, Speculative Design, and Prototyping

Within such a framework, teaching students to understand technologies (even those who may not be familiar with most of them, such as coding or prototyping) and how to become "fluent" with them (Lukens & DiSalvo, 2012) becomes crucial. It is not about creating expertise but rather literacy (Cangiano, 2016), which means being able to understand which tools can be the most suitable for translating a concept into an artefact. Students are not forced to fit their speculation into a predetermined media. Quite the opposite, they are encouraged to understand first the goal of their project and then explore the available technology to find the most suitable media for them, whether it is printed matter, a three-dimensional space, or a piece of code.

The proposed learning approach opens a space for intellectual exploration, demanding a tangible design translation to discuss and evaluate such speculation. Where design has been paradoxically left behind by its modernist promises (Colomina & Wigley, 2016), showing the limits of its deterministic spirit, it becomes necessary to re-think new roles for design itself

(Dunne & Raby, 2013). As sociologist Bauman (2016) states, in a post-modern society rife with uncertainties, it is in the ambiguity itself that a transformative potential can be found. "As design educators, we cannot afford to exclude Speculative Design from […] education of our students, especially after the current crisis that the whole world is experiencing" (Auger et al., 2021). As a pedagogical tool, Speculative Design opens students' minds to "think more creatively and critically about the role of design in our shared futures" and apply design principles in different contexts and types of projects. Most design educational programs still adopt "the modernist rational and functional understanding of design as a problem-solving discipline" (Auger, 2016). It is necessary and urgent for the designer to be trained to "reflect-in-action" to learn to be a "researcher in the practice context" (Schön, 1983, p. 68) and not just to solve problems. Mazè & Redström (2007, p. 10) affirmed that "rather than objective knowledge or abstract theory, conceived of as above or in advance of practice, such perspectives give primacy to subjective interpretation and practical experience". Moreover, Mitrović (2019) adds that "through imagination and critical thinking and by using design [...], Speculative Design practice inspires thinking, raises awareness, examines, provokes action, opens discussions and has the potential to offer alternative directions and positive shifts that are urgently needed in today's world. It is also significant that we can view this practice as a reflective approach that provides designers with the opportunity to reflect on the issues they are dealing with and, even more importantly, the practice itself. Through critical investigation, the creation of objects that generate a story, or through a story that is embodied in artefacts, Speculative Design attempts to anticipate the future, but at the same time assists in re-thinking and understanding our present moment."

These considerations appear to be a fitting premise for a teaching process at an undergraduate level aimed at integrating research into and through learning. It is a training level whose main objective is to allow students to acquire technical skills and a range of soft skills to be used in the professional field.

Coding and digital prototyping are encouraged, and computational and physical world integration is appreciated. However, using a specific technology is not mandatory: framing a design problem by choosing material, medium, or method first might limit possible solutions. On the other hand, coding and other digital technologies are languages that designers need to learn and use proactively and consistently.

Undergraduate students usually regard coding as a sector-specific, obscure practice. They rather learn to use the software as a static tool for their practices: the possibility to customize or to create new tools is still hardly accepted. By using closed software, "you'll never be able to examine what the programming code is actually doing, and if you want it to work differently, it's impossible for you to make changes to the software" (Maeda, 2019, p. 138). Bringing code within the toolset enables students to learn "procedural literacy" and no longer regard the computer as a mysterious "black box" (Crow, 2008). They (re)gain control of the technology.

In the professional context, computational design is misunderstood as a technical skill instead of being regarded as a way of thinking. According to Reas, it allows one "to think around and outside of the constraints of any specific piece of software – it makes it more possible to imagine and invent something new [...] the code is a means to an end, and the focus is on what the code creates or generates" (Cangiano, 2016).

Learning to code has set the conditions for new ideas and forms in the Communication

Design field. The point is that learning to program and engage the computer more directly with code opens the possibility of creating tools, systems, environments, and entirely new modes of expression. As a consequence, using the McLuhan metaphor, computer and digital technologies could cease to be tools and become media instead (Reas et al., 2010, p. 25). Moreover, it is crucial to consider accessibility to instructions and information related to programming languages offered by the global open-source culture as a critical component in this evolutionary process (Lehni, 2011; Antonelli, 2011b). This culture allows sharing of knowledge, responses, and codes, making a constant upgrade possible. Knowledge becomes available for all, blurring the boundaries of academic and professional disciplinary fields.

In a teaching context, the approach that does not consider acquiring skills and knowledge as separated fragments but as an evolutionary and iterative process appears more effective. The use of programming to start processes and develop applications is adopted as a key element of the toolset (Lehni, 2011). This approach allows the customization of some applications both at the development/prototyping and testing phases, which we can consider as steps of a reflection-in-action process, "providing continuous improvement and higher levels of assurance that solutions will be appropriate and effective" (Bowie & Cassim, 2016, p. 142).

We do not mean to replace or compete against traditional design tools and media but to enrich them and enhance the designer's technological imagination in order to produce multimodal forms of expression (Balsamo, 2010, pp. 4-7). This is possible by approaching with a thinkering attitude eventual new canvases for the designer. Some of these "new canvases" proposed during the Course are electronics and embedded programming with Arduino ecosystem, codes for visual output such as Processing, p5.js, and Three.js, digital fabrication, 3D modelling and printing tools. These help students to create concrete prototypes that "provide the crucial element of surprise, unexpected realizations that the designer could not have arrived at without producing a concrete manifestation of [...] (the) ideas" (Klemmer et al., 2006, p. 142). The prototype plays an essential role in terms of research purpose as well, so we can refer to it as a research artefact (Giaccardi, 2019; Zimmerman, Forlizzi & Evenson, 2007), or as a vehicle "for research about, for and through design" (Wensveen & Matthews, 2014, p. 262). Students in the second semester work on their final thesis developing research from these projects.

This variety of possible media and tools finds a breeding ground in Speculative Design, which is characterized by not belonging only to the design context and a particular set of rules or methods, opening to various methods, tools, techniques, and instruments as well as other practices and disciplines (Mitrović, 2019). According to Lukens & DiSalvo (2012, p. 32), "speculative design and technological fluency are cross-disciplinary and integrative". We can interpret the term "fluency" as the "ability to translate between domains and view the membranes separating areas of inquiry as porous" (Lukens & DiSalvo, 2012, p. 32). Bernstein (2011, p. 8) adds that "fluency with technology often draws on knowledge, skills, and approaches that cross traditional disciplinary boundaries".

Anti-Disciplinary Teaching Methodology

According to the belief that design is a tool to create ideas, not only things, students are involved in a process that moves from problem-solving to problem-finding. That encourages the development of concepts, scenarios, and responses without any predetermined function, aesthetic, or, as already discussed, boundaries in the use of technology.

The process is based on an anti-disciplinary and evolutionary idea of the educational design process, which does not rely on a fixed design method. Defining a teaching methodology as anti-disciplinary means "going one step beyond being multi-disciplinary" (Childress, 2016), avoiding strict specialization in Communication Design education. Adopting an anti-disciplinary approach could mean "not only working in one specific field, but rather instead drawing from elsewhere to imagine something new" (Brin, 2016). The pedagogical strategy, with its critical approach, "emphasizes alternative approaches to conventional problem-solving paradigms […] [including] both problem-seeking initiatives and problem-posing inquires" (Blauvelt & Davis, 1997, p. 80). Overall, the proposed methodology and educational objectives must consider that the Final Synthesis Communication Design Studio of the third year is the final one for the students. One of its peculiarities is that it is a Studio in which all the knowledge and skills acquired in the previous semesters must be used. Coding and prototyping are added to those related to the design of communication and visual systems. Overall, the final project allows students to deal with a hybrid, transversal dimension of Communication Design, not necessarily closed in a specific area.

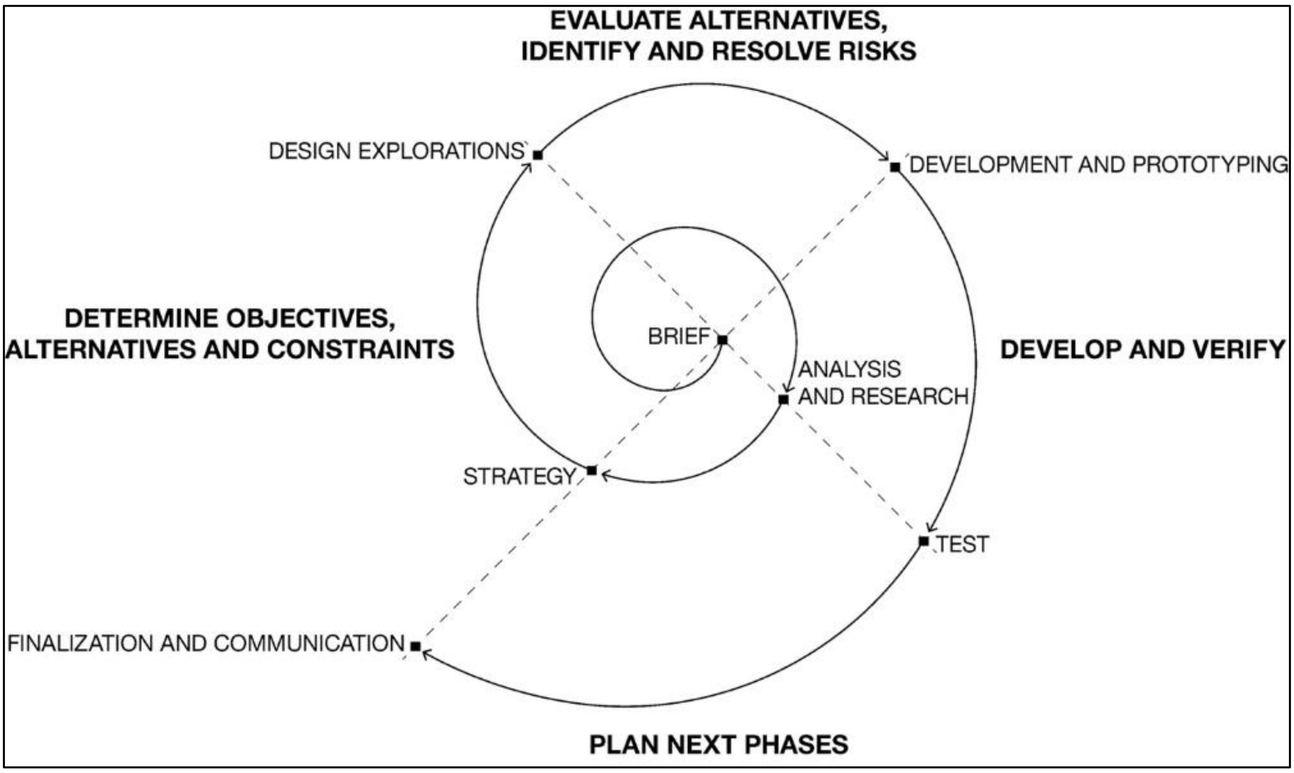


Figure 1: The methodology model.

The applied methodology can be visualized with a spiral model, which accurately represents repeating cycles of design moving away from a central starting point (Figure 1). It is inspired by the software development model by Barry Boehm (Dubberly, 2005, p. 122) with some modifications. The intention is to represent not a sequential process but a cyclical one emphasizing continuous improvement (Dubberly, 2005, p. 115). In each of the four main phases, students could experience different steps in the design process as they gradually approach their final project. Nevertheless, according to Frascara & Winkler (2008, p. 7), it is not “reduced to a mechanistic set of steps” because “method without imagination contributes very little to the design profession and the solution of complex design projects”.

Students work in groups of a minimum of 4 and a maximum of 6 people, considering the total amount of students increased from 55 to more than 60 per class in the last four years. Once the general theme is given (e.g., ‘death’, ‘rituals’, ‘daily data’), each group has to define a specific point of view on the theme and a scenario to work on: so they have to seek and find a problem to highlight and discuss through Analysis and Research. They use human superstructures and organizations as useful subjects to ‘represent’ their fiction through fictional branding to apply competencies and skills already acquired previously in the first two years of the Course.

The second step is to define a concept and a communication strategy and how to develop it in a multidimensional and multichannel dimension (touchpoints and selected media), as well as the Communicative Machine’s main functions, meanings, and contents. According to their concept and strategy, they must think and design a visual identity that can be consistently communicated in two- and three-dimensional outputs. By doing so, the students gain confidence in the design of complex systems.

The core activity is the prototyping phase which involves both digital and analog areas. They are encouraged to autonomously acquire the skills they lack, especially in the areas of digital design, coding, and prototyping. The teachers eventually support them in developing their projects better. Each member has a specific role within the group based on his/her interests and skills. A crucial element of this “critical pedagogy is the recognition, not the dismissal, of students’ social experiences and cultural affiliations, which serve as lenses through which they experience the world and are a reflection of the audiences we attempt to reach” (Blauvelt & Davis, 1997, p. 80).

The main outputs (Communicative Machines) are objects, installations, or interactive devices realized as prototypes to be verified and tested. These ‘machines’ should be intended as “object personas”: an extension of the design research and educational process arguing for design fiction as an important methodological tool. Design fiction represents a speculative mode of thinking that can disclose new questions and unconventional opportunities (Cila et al., 2015).

Prototyping Communicative Machines

“A work of speculative design is often an object […]. While prototyping deals with how an idea could be realized, speculative design asks what if that idea was prevalent in our society? Would we want it?” (Peace, 2019). The experimental projects presented here aim to “unsettle the present rather than predict the future” (Clark, 2011, p. 17).

Each one has been developed (from the concept to the final prototype) over a period of five months. These are results coming from various classes with different briefs. Each year, their projects are: exhibited (except during pandemic times) on occasions proper to test concepts and prototypes through a wide audience; exposed into a collective website or individual social network accounts so to share ideas, optimize presentation materials (e.g., photos, videos, texts) and verify that the audience can understand them without direct explanations.

Figure 2: In Loving Memory, A.Y. 2019-2020 (Authors: Gabriele Broggini, Chiara Carovelli, Emanuele Ceccherini, Eleonora Dussin, Bianca Fratin).

During the 2019-2020 Academic Year, the assigned central theme was ‘Death’ (http://morte13.labsintesi-c1.info/), an intriguing and demanding issue, especially considering that just after a few months we all fronted it directly because of the pandemic. Out of 13 projects, one seems to be consistent with the aims of the present paper. Starting from the “what if?” question “How long does the life of the objects we own last?”, the project entitled In Loving Memory (Figure 2) intended to discuss daily products planned and perceived obsolescence. Specifically, the strategy applied by several global corporations to reduce life to these objects, e.g., mobile phones, shoes, tights, or earphones. Instead of repairing them, consumers would rather throw them away because it is not economically convenient or a perfect excuse to change an old item with its new model, producing massive waste. The prototyped interactive memorial is dedicated precisely to these objects, telling their stories and explaining technical causes leading them to ‘death’. The installation allows users to activate various narratives available on web pages with texts, images, and short videos. The website also works as an archive of these stories, and users can add content. Each object stands in a niche of the memorial; when the user approaches a niche, a proximity sensor activates local LED lighting, highlighting the object. A QR Code allows the connection to the online archive. With its intentional monumentality, the project is proposed as a critical speculation on a contemporary problem, providing an interpretation of the general theme of death from the point of view of objects.

‘Rituals’ was the assigned theme for the Academic Year 2020-2021 (http://retuals.labsintesi-c1.info/). The aim was to investigate human rituals in conditions of remote distances and forced online connections. Of course, the pandemic effect conditioned the choice, but the rituals considered allowed to envision, in some cases, new needs and behaviours.

TOD (Figure 3), a sort of home device, intended to speculate on the ritual of dead commemoration, starting from the question, “what if commemorating the dead was an evaluated performance?”. Tod blends into the environment and the everyday life of its users just like every high-tech device. It guides the user to the proper commemoration of the dead by suggesting the right frequency and execution. The Core symbolizes each deceased person; it is a portable device made ‘alive’ by the glow of an ever-changing luminous ‘wisp’. The user can perform the memorial service by placing it in his home hub and periodically performing three tasks: Contact, Conversation, and Remembrance. In this case, the speculation moves from a pure critical goal to a ‘future design’ one, assuming the possibility of such a home ritual. The prototype developed allowed: 1) to test the user journey, fixing the digital interface functionalities and flow, 2) to verify the impact and agency of the object itself with an external audience inserting it in videos that supported the project presentation, involving people outside the School.

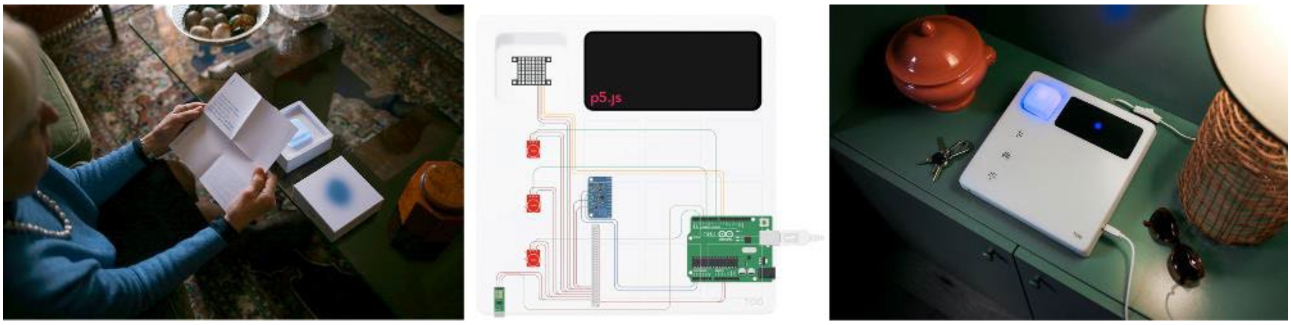


Figure 3: TOD, A.Y. 2020-2021 (Authors: Giovanni Bonassi, Martina Bracchi, Silvia Casavola, Donato Renzulli, Tommaso Stragà, Matteo Visivi).

The object was created by thermoforming a sheet of PETG, subsequently finished with a soft-touch paint; some sensors make it possible to activate the various commemorative functions managed overall through a mobile phone used as hardware to take advantage of the touchscreen. Finally, the CORE of the device (the smallest cube, symbol of the soul of the deceased) has inside a matrix of sixty-four LEDs (Adafruit DotStar High Density 8x8 Grid) which light up individually to obtain a ‘wisp’ effect which also characterizes the visual identity.

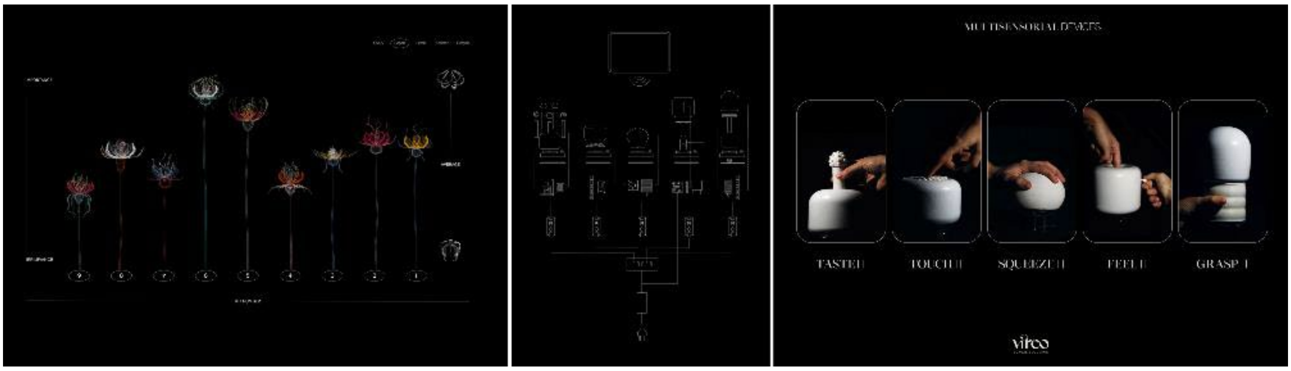


Figure 4: Vireo. Sexual Blooming, A.Y. 2020-2021 (Authors: Alessandro Gori, Lara Macrini, Matteo Paoli, Caterina Ramilli, Simone Restifo Pilato).

Instead, Vireo (Figure 4) investigated and discussed the ritual of ‘sexual blooming’ by conceiving an interactive kit allowing users to express and share individual sensations, memories, and impressions. The user is asked to question his interpretation of this fundamental passage in life through five different devices. Each device stimulates sensations that vary in intensity and, depending on the user’s choices, are translated into data that give the experience a visible form. As a final output, a unique flower is produced for each user. The flower shapes, colours, and parts change according to the inputs received by the user. The flower is a metaphor for a new language and becomes a means of sharing and comparison with other users who interface with the kit. Each user, through a website, can compare his/her personal output across three different views that provide new interpretations of the experience. In the speculation scenario, the Vireo flower becomes the new way of expressing oneself to talk about one’s virginity without limits due to a one-way vision. The speculation intends to provoke the audience on an intimate issue that is exposed in various cultures through various kinds of rituals but, at the same time, not publicly shared in contemporary societies.

The kit was developed using a variety of sensors and actuators to obtain a system of multi-sensory interfaces that stimulate and interact with the user in various ways, including sensations of heat, vibrations, sounds, and lights, in order to achieve a high degree of involvement and complete immersion during use. A USB Hub manages the five objects’ interactions, and a wireless display gives feedback to the user, visualizing the individual flower. In this case, the prototype was developed to support an original narrative consistently in two dimensions. A material one that includes the five devices referring to the senses. And a digital one, with the programming of the website interface and the visualization of the single representations (the individual ‘flowers’) obtained using the Blender 3D modelling software. The result is an essential part of the learning process, helping to verify the acquisition of specific technical skills and the transversality in using knowledge.

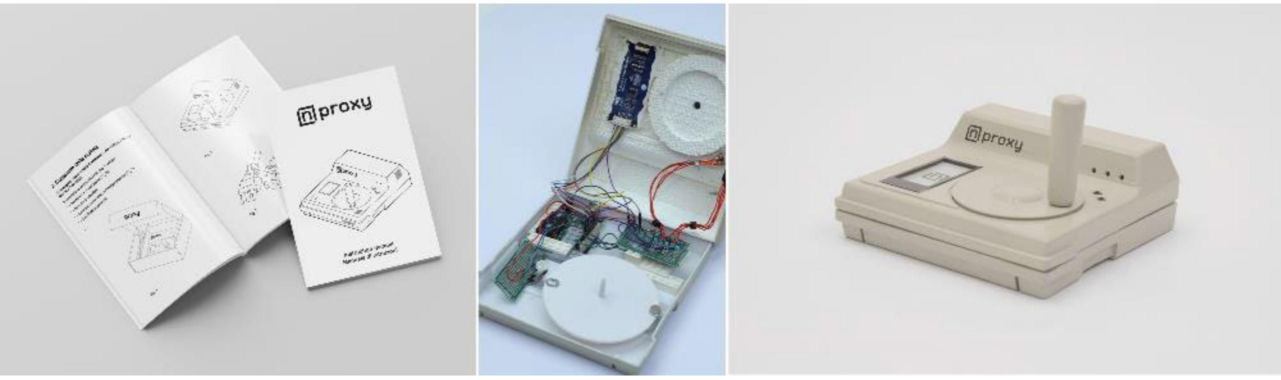


Figure 5: Proxy by Nextnet, A.Y. 2021-2022 (Authors: Andrea Avanzi, Lorenzo Baraldi, Samuele Cellura, Andrea Nodari).

Finally, during the Academic Year 2021-2022 (http://fattididati.labsintesi-c1.info/), having as the main theme ‘Daily Data’, another home device, named Proxy by Nextnet (Figure 5), intended to speculate on the impact of the internet on the environment. The internet machine consumes energy and produces tons of CO_2 daily, although people continue to see it as ethereal and pure. In a fictional future plagued by an economic and social crisis, the ecological impact of the internet is out of control. Each country is forced to ban the internet planetwide, and Nexnet Proxy is the only device capable of generating connection through user effort. A display visualizes the quantity of web connection available and the possible kind of digital data the user can access (e.g., video, social network, files’ weight). Although the scenario may appear simplistic, it is possible to position Nextnet as a critical-speculative project, imagining a possible future that could also be an alternative present, considering the current conditions of our planet.

Also, in this case, the prototype was developed to support the scenario and narrative consistently. The 3D-printed object was completed with an Arduino board connected to a Hall sensor and low-energy consumption display. The prototype is connected to a computer to manage the data collected from the sensor and transmit them to the Nextnet website.

Discussion and Some Conclusions

The four shortly discussed projects developed using the presented pedagogy process generated responses in the meaning of Frascara (Frascara & Winkler, 2008, p. 11): design reduces problems and should always involve research. These were realized starting from different points of view, developing different scenarios, and using various technologies and media, no matter if analog and/or digital. A natural consequence is that each design has to be theoretically discussed and physically verified by making prototypes. Students are pushed to experiment with visual expressions, user experiences, and tangible interactions between two and three dimensions, inevitably involving the fourth, the one of time. Students unveil unconventional approaches to the project and explore alternative design values, forms, and representations (Johannessen, 2017; Bardzell & Bardzell, 2013).

Speculation and critical stances were translated actively using Communication Design but approaching design solutions as a hybrid discipline, that means it "allows to break out of traditional typologies, to experiment with hybridizations of formats, structures, and modes of expression" (Quaggiotto & Galasso, 2023, p. 220). By adopting this approach, students are led to assume a critical attitude towards their position as designers, reflecting their practice's social and political implications. Moreover, they also get used to managing their professional field as an open context, not necessarily closed by disciplinary boundaries but evolutionary by nature. Design speculations are not meant to give answers and certainties; they aim to imagine new questions and reflect on contemporary and future times. They experienced a learning path that intends to go beyond the centrality of *téchne* to encourage the wielding of knowledge.

The prototyping phase is considered significant since, beyond the reasons already explained, it generates organizational capabilities such as flexibility and requisite variety, becoming integral to products and processes. It also operates as an antidote against core rigidities through updates of new knowledge and new methods for solving problems (Leonard-Barton, 1995; Berglund & Grimheden, 2011). According to Berglund & Grimheden (2011), the knowledge spiral model allows students to add benefits to teamwork, utilizing each other experiences and perspectives, integration and synthesis, and socializing.

The material and/or digital prototype artefacts play an essential role in introducing students to a Research through Design (RtD) attitude (Zimmerman, Forlizzi, & Evenson, 2007). According to some of Giaccardi's (2019) statements, they play intriguing and essential roles in demonstrating possibilities, provoking and speculating on alternative presents or futures, evaluating design outcomes, and empirically testing hypotheses. Certainly, their development cannot be reduced to a single objective.

The feedback collected over the years, both from students and during occasions of sharing with a broader audience (e.g. exhibitions, websites, social networks), confirm the effectiveness of the learning process and educational experimentation aimed at creating working prototypes. Students appreciate the anti-disciplinary approach in acquiring new knowledge and skills, directly verifying communication design's hybrid nature. At the same time, they learn to learn, accepting the challenge of a constantly evolving discipline and practice. In the comments to the various editions of the Communication Design Studio, they define the design approach as "extremely innovative" and "useful to learn by doing, work more independently and deal with technologies never used before". Furthermore, the assignment of issues to develop through a speculative approach is interpreted as "stimulating" and "a challenge", which allows them to "find unconventional design solutions".

The practical verification, made with an external audience to that of the School, finally makes it possible to verify the design hypotheses through the prototype. Its role is crucial to allow an audience to understand the design narrative through direct experience. For students, this phase can be critical for questioning the design hypothesis. However, it also becomes the moment for self-criticism, for reflection on what has been achieved.

It is our firm belief that an anti-disciplinary way of working and designing should be encouraged, especially during students' education so to train them to break disciplinary fields, to look to knowledge and technology with an open mind, to be better designers and citizens able to manage and react to uncertainties.

Acknowledgements

The author would like to thank the teachers and colleagues who worked during the last years at the Final Synthesis Communication Design Studio C1, Bachelor's in Communication Design, School of Design, Politecnico di Milano: professors Andrea Braccaloni, Pietro Buffa, Alessandro Masserdotti and Giacomo Scandolara, the assistants Marcello J. Biffi, Alberto Candido, Antonio Garosi, Michele Invernizzi, Adele Mazzali, Andrea Pronzati, Claudia Tranti, Ernesto Voltaggio. Launching, managing, and sharing an anti-disciplinary design practice in an educational context has been possible with them. Consequently, a grateful thought is for all students who, over the years, accepted the challenge.

References

Antonelli, P. (2011[a]). Talk to me. In E. Hall (Ed.), Talk to me. Design and communication between people and objects *(pp. 6-16). New York: Museum of Modern Art.*

Antonelli, P. (2011[b], July 4). States of Design 03: Thinkering*. Domus Web.* https://www.domusweb.it/en/design/2011/07/04/states-of-design-03-thinkering.html

Armstrong, H. (2009). Graphic Design Theory: Readings from the Field*. New York: Princeton Architectural Press.*

Auger, J. (2016). Speculative design is a counter to normative design [Interview]. *Speculative – Post-Design Practice or New Utopia?.* http://speculative.hr/en/james-auger/

Auger, J., Hanna, J., Helgason, I., Mitrović, I. (Eds.). (2021). Beyond Speculative Design: Past – Present – Future*. Split: Arts Academy, University of Split.*

Balsamo, A. (2009). Design. International Journal of Learning and Media*, 1(4), 1–10.* http://dx.doi.org/10.1162/ijlm_a_00036

Bardzell, J., & Bardzell, S. (2013). What is critical about critical design?. In S. Bødker, S. Brewster, & W. E. Mackay (Eds.), CHI '13: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems *(pp. 3297–3306). New York: ACM.* https://doi.org/10.1145/2470654.2466451

Bauman, Z. (2016). Scrivere il futuro*. Rome: Castelvecchi.*

Berglund, A., & Grimheden, M. (2011). *The Importance of Prototyping for Education in Product Innovation Engineering. In A. Chakrabarti (Ed.),* Research into Design — Supporting Sustainable Product Development *(pp. 737-745). Singapore: Research Publishing.*

Bernstein, D. (2011). Developing technological fluency through creative robotics *[doctoral dissertation, University of Pittsburgh]. D-Scholarship @ Pitt. http://d-scholarship.pitt.edu/8780*

Blauvelt, A., & Davis, M. (1997). Building bridges: a research agenda for education and practice. In M. Beirut, W. Drenttel, S. Heller, & DK. Holland (Eds.), Looking Closer 2 *(pp. 77-81). New York: Allworth Press.*

Bowie, A., & Cassim, F. (2016). Linking Classroom and Community: A Theoretical Alignment of Service Learning and a Human-Centered Design Methodology in Contemporary Communication Design Education. Education As Change, 20*(1), 126-148. https://unisapressjournals.co.za/index.php/EAC/article/view/556*

Brin, S. (2016, November 2). Making/Meaning in the Realm of Anti-Disciplinarity. *opentranscript.org. http://opentranscripts.org/transcript/making-meaning-antidisciplinarity/*

Bucchetti, V. (2020). È design della comunicazione. Ocula. Occhio semiotico sui media, 21*(24), 116–126. http://dx.doi.org/10.12977/ocula2020-44*

Cangiano, S. (2016). Coding as a way of thinking – Interview with Casey Reas. Progetto Grafico, 13*(30), 10–19.*

Childress, J. (2016, May 26). Head, Hands, Heart & Voice. *justinchildress.co. https://justinchildress.co/head-hands-heart-voice*

Cila, N., Giaccardi, E., Tynan-O'Mahony, F., Speed, C., & Caldwell, M. (2015). Thing-Centered Narratives: A study of object personas*. 3rd Seminar Research Network for Design Anthropology. Aarhus: The Research Network for Design Anthropology. https://www.researchgate.net/publication/305781838_Thing-centered_narratives_A_study_of_object_personas*

Clark, S. R. L. (2011). Philosophical Futures*. Frankfurt am Main: Peter Lang.*

Colomina, B., & Wigley, M. (2016). Are we human? Notes on an archaeology of design*. Zürich: Lars Müller Publishers.*

Crow, D. (2008). Magic box: craft and the computer. Eye, 18*(70). http://www.eyemagazine.com/feature/article/magic-box-craft-and-the-computer*

Dubberly, H. (2005). How do you design? A compendium of models*. San Francisco: Dubberly Design Office. http://www.dubberly.com/wp-content/uploads/2008/06/ddo_designprocess.pdf*

Dunne, A., & Raby, F. (2013). Speculative everything. Design, fiction, and social dreaming*. Cambridge (MA): MIT Press.*

Frascara, J., & Winkler, D. (2008). Jorge Frascara and Dietmar Winkler. On Design Research. Design Research Quarterly, 3*(3), 4-14. https://dl.designresearchsociety.org/design-research-quarterly/8/*

Giaccardi, E. (2019). Histories and futures of research through design: From prototypes to connected things. International Journal of Design*, 13(3), 139–155.* *http://www.ijdesign.org/index.php/IJDesign/article/view/3192/875*

Grimaldi, P. (2009). Blur Design. BlurDesign*, 1(0), 21-39.*

Harari, Y. N. (2014). Sapiens: a brief history of Humankind*. London: Harvill Secker.*

Ito, J. (2016). Design and Science. Can design advance science, and can science advance design?. Journal of Design and Science*, 1.* *https://doi.org/10.21428/f4c68887*

Johannessen, L. K. (2017). The young designer's guide to speculative and critical design*.* *https://www.ntnu.edu/documents/139799/1279149990/16+TPD4505.leon.johannessen.pdf/1c9221a2-2f1b-42fe-ba1f-24bb681be0cd*

Klemmer, S. R., Hartmann, B., & Takayama, L. (2006). How Bodies Matter: Five Themes for Interaction Design. In S. Bødker, J. M. Carroll, & J. Coughlin (Eds.), Proceedings of the 6th conference on Designing Interactive Systems *(pp. 140–149). New York: ACM.* *http://doi.acm.org/10.1145/1142405.1142429*

Lehni, J. (2011). Teaching in the spaces between code and design. Eye*, 20(81).* *http://www.eyemagazine.com/feature/article/teaching-in-the-spaces-between-code-and-design*

Leonard-Barton, D. (1995). Wellsprings of Knowledge —Building and Sustaining the Sources of Innovation*. Boston (MA): HBS Press.*

Lukens, J., & DiSalvo, C. (2012). Speculative Design and Technological Fluency. International Journal of Learning and Media*, 3(4), 23-40.* *http://dx.doi.org/10.1162/IJLM_a_00080*

Maeda, J. (2019). How to speak machine. Computational thinking for the rest of us*. London: Portfolio.*

Mazé, R., & Redström, J. (2007). Difficult forms: critical practices of design and research. In S. Poggenpohl (Ed.), IASDR07. International Association of Societies of Design Research Conference Proceedings *(pp. 1–18). Hong Kong Polytechnic University.* *https://www.sd.polyu.edu.hk/iasdr/proceeding/papers/Difficult%20forms_%20Critical%20practices%20in%20design%20and%20research.pdf*

Mitrovič, I. (2019, July 22). New Reflections on Speculativity*. Speculativeedu.* *https://speculativeedu.eu/new-reflections-on-speculativity*

Peace, E. (2019, July 24). Speculative design for the real world. How speculative design methods can drive innovation*. Uxdesign.cc.* *https://uxdesign.cc/speculative-design-for-the-real-world-551130b22827*

Quaggiotto, M., & Galasso, C.S. (2023). Designing hybridization: Alternative education strategies for fostering innovation in communication design for the territory. *In Z. Adil (Ed.), A Focus on Pedagogy: Teaching, Learning and Research in the Modern Academy (pp. 218–226). Amps.* *https://amps-research.com/wp-content/uploads/2022/12/Amps-Proceedings-Series-28.2.pdf*

Reas, C., McWilliams, C., & Barendse, J. (2010). Form+code in design, art and architecture*. New York: Princeton Architectural Press.*

Schön, D. (1983). The reflective practitioner: how professionals think in action*. London: Temple Smith.*

Triggs, T. (2003). The typographic experiment: radical innovation in contemporary type design*. London: Thames & Hudson.*

Wensveen, S., & Matthews, B. (2014). Prototypes and prototyping in design research. In P. Rodgers, & J. Yee (Eds.), The Routledge Companion to Design Research *(pp. 262–276). London: Routledge.*

Zimmerman, J., Forlizzi, J., & Evenson, S. (2007). Research through design as a method for interaction design research in HCI. In M. B. Rosson, & D. Gilmore (Eds.), Proceedings of the Conference on Human Factors in Computing Systems *(pp. 493–502). New York: ACM. https://doi.org/10.1145/1240624.1240704*

Francesco E. Guida

MSc in Architecture and PhD in Design and Technology for the Enhancement of Cultural Heritage. He is an associate professor at the Department of Design and teaches Communication Design at the School of Design, Politecnico di Milano. He is the Secretary of the Communication Design Courses.
He has been involved in visual communication since the early nineties and publishes contributions on visual communication and other related issues in journals, books and conference proceedings.
Previous board member of AIAP (Italian Association of Visual Communication Design), he is the scientific coordinator of the Graphic Design Documentation Centre. Past associate editor of the journal «AIS/Design. Storia e Ricerche» (gaining an honourable mention at the XXVII Compasso d'Oro, Category: Theoretical, Historical, Critical Research for the issue 12/13 (2020) entitled "Social Design. Design and the Common Good"), he is an editorial board member of «PAD. Pages on Arts and Design».

Prototypes, translation and research in social design education

Alvise Mattozzi, Department of Environment, Land and Infrastructure Engineering and TheSeUs, Interdepartmental Research Center on Technology Society and Humanity, Politecnico di Torino IT
Jonathan Ventura, Department of History and Philosophy of Design, Shenkar – Engineering. Design. Art Ramat-Gan IL

Abstract

In this paper, we propose to look at designing processes as interpretive acts of translations parallel to other various descriptive and iterative artifacts – briefs, mood boards, sketches, post-it boards, design drawings, technical drawings, user journey-maps and diagrams, renderings, mock-ups, etc. – and to look at what roles prototypes play within these processes of translation. More specifically, the role of prototypes within processes of translation will be investigated by looking at social design and especially in social design education projects.
Indeed, whereas prototypes have served designers for many decades to consider alternative outcomes, test out various approaches, and evaluate ergonomic needs and constraints, in social design, as part of participatory or codesign practices, prototypes offer even more potential for harnessing communities, mediating between various stakeholders, and highlighting a more relevant path for the design team. In a similar manner, in design education, prototypes are not only used to highlight the various stages of the design process but also the importance of the different design partners and stakeholders. Furthermore, prototypes can serve to highlight key values and ideologies relevant to a specific design strategy to articulate and enhance the designer's role in their local and professional communities. By using translation to link these spheres of knowledge, we will highlight an innovative approach to understanding the importance of prototypes in social design education.

social design; prototype; education; design research; semiotics

Introduction

There is a widespread agreement – also acknowledged by the call for paper of this conference – on the fact that, among the cascade or cloud of inscriptions, representations (Armando and Durbiano 2016; Beaubois 2015), or "descriptive artifacts" (Mattozzi 2019) – i.e. various iterations of the brief, mood boards, sketches, post-it boards (or their digital versions, such as Miro), drawings, technical drawings, diagrams focused on users journeys, renderings, mock-ups, etc. – that characterises designing processes, prototypes tend to come in the "later phases" (Sanders and Stappers 2014) or "far advanced in development" (Marcus 2014) of the designing process. Moreover, it is also widely acknowledged that prototypes allow experimentation (Corsin Jimenez 2014; Marcus 2014), by providing a possible, but still open to revision, configurations of what the desired outcome of the designing process should be.

The specificity of such experimentation lies in the fact that through prototypes “others”, i.e. people not part of the design studio or of the design process, like various kinds of stakeholders, potential users (design partners, as they are termed in the UK) or manufacturers can be involved through the presence of the prototype “on the table” (Stappers 2007) and engaged in the design process, producing “focused discussions” (ibid) and feedback, thanks also to the fact that the prototype can be tested by “confront[ing] the world” (ibid), also through trials of usage.

In this paper, we will take into account all these issues through the notion of “translation”, showing the relevance of this notion in order to understand design, and specifically the role of prototypes, through examples taken from design projects carried out within social design courses.

Therefore, the paper will also propose a reflection on the role of prototypes within social design education.

Translations within designing

We assume the design process as a process of iterative translations taking place from one of the “descriptive artefact” (brief, mood boards, sketches, post-it boards, drawings, technical drawings, diagrams focused on users journeys, renderings, mock-ups, etc.) we mentioned in the introduction, to the other. Of course, within this iterative process prototypes play a crucial role.

By translation, we mean the passage from a configuration (be it verbal, visual, tangible, etc., or a combination of all these options) to another configuration through the mediation of a third configuration, even just an imagined or “mental” one, within a process akin to the one of the Peircian sign. The third configuration – the mediating one – identifies, highlights, extracts, hierarchize and reconfigure features of the first configuration into the second one – a process that is usually intended as interpretation. Take, for instance, the passage from a sketch of a product to a prototype through a rendering: the rendering will keep only certain features of the sketch, adding others features, which in turn will influence the prototype. Of course, the translation between the sketch and the rendering is in turn mediated, and thus translated, by other possible configurations, for instance the configuration reconstructed “mentally” by the user and then the one articulated by the constraints and opportunities provided by the 3D modelling software. Or, take the passage from a brief to a sketch: it can be mediated by the configuration created by the set of products similar to the one mentioned in the brief found through a research on the internet (Ventura and Ventura 2015). Or, take the passage from a mock up of a seat to the prototype: it can be mediated by the configuration created by various materials and the body of a craftsman who is in charge of finding the right material and tries them out on his own body (Parolin and Mattozzi 2013).

As we can see, translations within designing are dense iterations of mediations, within which in between two configurations you can always find another one carrying out a translation.

To achieve these various modes of translation, designers enact several phases of key systems of interpretation, including a visual-material one (through semiotic denotations), a hermeneutic one, and the intricate understanding of the relation between design decisions and its manifestation of experiences, memories, feelings etc. (through a phenomenological basis). This understanding enables designers to incorporate in the mediating configurations the socio-cultural behaviours of individuals and communities involved in and through the project or intervention, as well as – key issue for social design projects – social values and ideologies. These are translated into the project, both from a theoretical and ethical stance and from a practical stance through the collaboration of the design partners, using codesign and participatory design practices.

Prototypes as translations

Prototypes as special translations within the designing process

Not dissimilarly from other "descriptive artefacts", prototypes take part in the translation processes in two ways: a prototype 1) is the translation of previous steps of the designing process in a temporary stable configuration 2) it prompts further translations that take the form of feedback, indications, and requests for revisions, which will likely lead to a new version of the prototype, when not to a revision of a portion of the designing process, going upstream the cascade of descriptive artefacts.

However, differently from other "descriptive artefacts", prototypes come toward the end of the designing process, as we already noticed in the introduction, with reference to Sanders and Stappers (2014) and Marcus (2014). Therefore, prototypes need to carry out a translation that somehow summarizes and builds on all the previous translation by providing a temporary stable configuration, which gathers and articulates most of the features of what should be the actual output.

Seen in this way, prototypes carry out something more than one of the iterative translations punctuating the designing process, given that it enacts a version of the final configuration of the design project or intervention. Around it, others – other people besides those who have taken part to the designing process and who have a specific expertise related to design in general or to a specific designing process, like stakeholders of various kind, users or design partners, manufacturers – can be gathered and, through it, can be engaged and involved, at various degrees, within the designing process.

Therefore, prototypes open up the designing process to others, and through such opening trigger social change (Sanders and Stappers 2014). Such opening up provides prototypes with their experimental relevance, i.e. the possibility of "confronting the world" (Stappers 2007) through trials and verifying if what designed "works" or not. But not only. The experimental relevance of prototypes regards also opening up, in turn, other possible ways of designing and, hence, revisions of the designing process and the very design project – this second opening takes place especially if what designed does not seem to "work" or to fully "work".

Such double opening – opening the design process to "others" and through it opening it to revisions – is key for social design, given its commitment to work for and with communities and to be sensitive to their values, points of view and dynamics.

Thus, prototypes are key steps in processes that tend to involve and engage communities, like those related to social design. Indeed, apart from using the prototype to check, reflect or validate a design concept, a prototype can serve as a steppingstone in co-designing, through which community members interact with the design team.

Prototypes as translation: from many to one

Seen in the way we are outlining, prototypes are something more than just the translation from a vague and abstract idea into a concrete, visualized and materialized output – as somewhat suggested by the call of this conference. Whereas the cloud made up by the various descriptive artefacts (brief, sketches, mood boards, technical drawings, rendering, post-it boards, journey diagrams, etc.) constituting the previous steps of the designing process can seem, taken as a whole, vague and chaotic and can seem to outline a vague and more or less abstract idea of the design project or intervention, each instance is in itself definite, characterized by its own details, and concrete.

Thus, the translation prototypes achieve does not go so much from the abstract to the concrete, but mainly from various scattered and multiple concrete instances to one collecting and connecting many of them and many of their features in an, often operational, whole.

Prototypes as translation in design education

The specific role prototypes play in designing processes seen as translations is of course key also within design education – and, indeed, as Sanders and Stappers (2014) remarked that prototypes can let students understand the importance of theory in design practice and education.

Given that, in a prototype, students need to translate many of the previous translations, articulating them in one, usually material, manifestation, they often find themselves encountering, for the first time, disparate issues – e.g., issues of weight, ratio and ergonomics, just to name a few – they need to articulate all at once.

We need also to consider that, differently from professional practice, where prototypes can end up being the last step of the designing processes, but usually are the step before making and manufacturing, i.e. the process which will lead to the final output as a product, an actual service or an intervention, within education, prototypes are usually the final output of a designing process taking place in a studio course or in a thesis design research process. Thus, within education, prototypes notoriously prompt a very specific final translation: a judgment by teachers.

Usually such judgment is mediated by a theoretical, social, and practical professional debate between student and teachers and among teacher themselves.

Prototypes' relevance for social design

In our view of the prototype incorporates several attributes: first, a prototype is key in bridging different social groups; second, a prototype is crucial when conducting design research in general, but more so when working in the field of social design; third, a prototype is a crucial element in design research, not only from a practical point of view, but to test and integrate theoretical knowledge; and finally, a prototype is a quasi-ethical tool helping the designer to step out of their professional stronghold and confront other cultural norms and constraints.

Prototypes in social design education

To bolster our claims, we wish to turn to several examples of students' works gathered through various cases taken from student projects of undergraduate and graduate programs in Hadassah College, Shenkar College, and the Master in Eco-Social Design of the Free University of Bozen-Bolzano.

As for the present paper, we do not intend to compare the various projects or the three education programs, but just to present different cases that we have experience of as teachers and supervisors, through which we can show how prototypes work as translations and prompt for further translations. Their unique attribute through social design focus will further enhance our approach to education strategies.

The first three cases come from thesis discussed at the Graduate Program of Interdisciplinary Design at Shenkar, whereas the fourth and the fifth from thesis discussed within a 4 years undergraduate program in inclusive design at Hadassah Academic College. Nevertheless, both share the same principles: during the last year of their studies, students conduct a lengthy theoretical and empirical process parallel to their final year project. This in turn is made of 4 parts: 1. An in-depth theoretical and/or historical research meant to outline the field of research. This can include the history of an object, socio-cultural attributes of a process, or general relevant theories from adjunct disciplines (behavioural psychology, educational philosophy, social attributes of occupation therapy, etc.). 2. Empirical research, focused on managing and manufacturing new knowledge through active research which includes ethnography, shadowing, visual/material content analysis, qualitative questionnaires, and more. 3. Added advanced research processes which include co-design or participatory design and validation using various prototypes. 4. Characterization of the designed project, including explaining every design decision, and in-length reflection as well as interpretation of the major innovation junctions of the project.

The last three cases come, instead, from the first introductory semester of the Masters in Eco-Social Design of the Free University of Bozen-Bolzano. This first semester introduces students coming from very different bachelor backgrounds – mainly design related, but not necessarily – to social design. The introductory design studio course brings together teachings related to product and spatial design (3D artifacts), communication design (2D artifacts), and Design Research. This effort has been carried out in collaboration with Officine Vispa (https://officinevispa.com/), an NGO working in community development instigating projects for Bozen-Bolzano's peripheral neighbourhoods, such as Don Bosco and Casanova-Kaiserau. From the get-go, students are familiarized with social design and are acquainted with the neighbourhood through visits and meetings with residents. As classes are manily conducted in the neighbourhood rather than at the university, students have more time to conduct deeper ethnographic explorations of the neighbourhood and its residents, while applying various relevant design research methodologies. Based on this, students need to develop design projects for and with communities, often focusing on the issue of care. These design projects end with a prototype that is used in three ways: first, as part of an exhibition aimed at the entirety of the neighbourhood's residents, including people not directly involved in a specific project, sharing ways by which the neighbourhood could be transformed for their benefit; second, as a prototype to be assessed by the Municipality, who partially finances the project, to understand if anything can be actually developed, manufactured and integrated into the neighborhood; third, as an artefacts around which the final examination takes place.

Prototype as Self-Enactment

In her graduate final year program, fashion designer Eden Ben Ami focused on the negative and positive traits of the historical corset vis-a-vis the socio-cultural perception of the feminine body. After a lengthy historical, theoretical, and empirical research (including interviews with fashion designers and qualitative questionnaires), Ben Ami continued to conduct an in-depth period of auto-ethnography. In this innovative period, she reproduced the historical corset and used it in her daily chores for whole days and recorded her physical, emotional, and psychological reflections on its use. Surprisingly, her research refuted classic myths regarding the corset including death at a young age, physiological damage, objectification of the feminine body, and being forced to wear it by decree of male family members (see Gibson, 2020). In her brief, Ben Ami concluded that since the historic corset was aimed for a standing position, it would be extremely valuable for a society that suffers from physical ailments due to lengthy periods of sitting motionless at workstation (a fact intensified since the COVID-19 lockdowns).

Figure 1: Eden Ben Ami's corset

The auto-ethnography research started with the reproduction of a classic 19th-century corset, wearing it daily and reflecting on the experience in a journal. As the hours spent wearing the corset grew, so did the time it took Ben Ami to wear the corset shortened from 15 minutes to 3, then to 20 seconds. Gradually she noticed changes in the way her body positioned itself and the ways it reflected her posture and relation to the outside world. Indeed, as a fashion designer working hours leaning over a sewing machine ending with an aching lower back, the corset eliminated these aches. While a positive change was the strengthening of the core muscles, a negative change was rib aches, due to a wrong measuring of the corset, resulting in Ben Ami shortening it by a few centimetres. Altogether, she spent over 1500 hours wearing the corset, leading to redesigning it and shifting its design till it reached the smallest shape that would still produce the same effect.

In other words, in this case, the prototype served a dual purpose. First, to reflect on classic functional design dilemmas relating to shape, size, material etc. However, the second purpose is the crucial one. In this case study, the act of translation was not only the dialogue between corsets as have been developed and used through history and the final project, but a translation of norms, conventions, and embodiment, mediated by her body and her practices. Such translation resulted not only in the rejection of contemporary perception of this object but in harnessing this product for a new understanding of both the feminine body, as well as a professional practitioner, and the intricate relation between labour and her body.

Figure 2: The corset in detail

Prototype as Function Testing

Typically, prototypes used in architecture or urban design are scaled down, thus focusing on an act of translating both the scale, as well the aesthetics and functionality. In her graduate project, Gilat Blum searched for a design system meant for a liminal area on the seafront of Tel Aviv. As in other Mediterranean seafront cities, the sea strip of Tel Aviv is characterized by a very narrow strip of sand, not very far from residential and commercial urban surroundings. Likewise, the climate is very dry, hot, and humid, raising the issue of designed shading solutions, as well as the classic needs of residents and tourists out for a fun day on the beach. After an in-depth research period including observations, interviews, and qualitative questionnaires, Blum designed a set of shading solutions and public furniture made of sand and other organic materials. Following her research, Blum understood that this site of “urban nature” needed to cater to different communities - tourists, parents of young children, teenagers, runners, people meditating or exercising Yoga, etc. These required solutions to their differing needs, such as a sun/shade ratio, privacy/commonality, and quiet space/lively atmosphere, as well as a preference for different hours throughout the day. These helped define her brief to design a flexible solution that would also be sustainable and cheap to manufacture and maintain. Her various models, ranging in materials and layout helped in this dual translation. Her solution rests on the municipality’s diggers that will transform sand into designed shapes and harden the sand through sustainable chemical solutions (see Hurkxkens, 2020), then fitted with 2D perforated textile sheets for shading. Thus, each temporary construction crumbles back at the end of the day, allowing for different shapes the next day, according to varying needs and the number of different visitors.

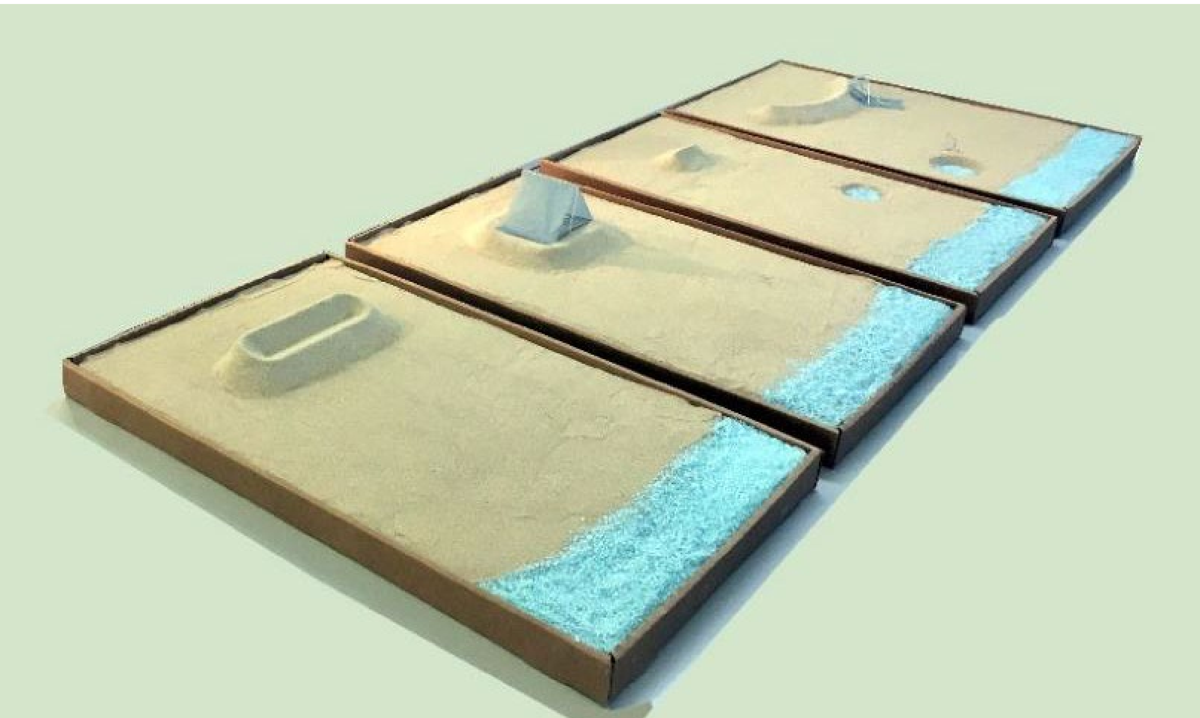


Figure 3: Gilat's scaled prototype for the coastline of Tel Aviv

In another seemingly functional project, designer Noa Matityahu used her relationship with her grandmother to offer an inclusive solution for the elderly, following COVID-19 the rising epidemic of acute loneliness among the elderly population. Through her prototype, Matityahu focused on four challenges the elderly is often faced, especially so during a lockdown or when family members are living far away from their residence: loneliness, the fear of new technologies, keeping a constant connection with family members, and a need for keeping one's fine motor control skills. In this case, as well, apart from functional testing, the prototype served to focus on key attributes and values of inclusive and social design – low-cost and preferably low-tech solutions; bespoke design, emanating a sense of style and high-end design, yet low-cost manufacturing; easy to use; and a designed product offering a plethora of functions. The main material in this product is wood - which connects to simplicity and warmth, and a single horizontal hinge alludes to backgammon board games which are very common among Israelis from all age groups. The user then chooses a design pattern to begin embroidering along the chosen lines. The interesting addition is that upon placing a tablet in the designated area, the elderly person shares their pattern with family members, thus enabling a mutual activity adding an actual conversation, and working together on the same project. The gentler the pressure, the more accurate would the final result be. Thus, the prototype in this example works on four different layouts, while translating the core values of social design - designing for what matters, working with and for social groups, and focusing on other values that the monetary one.

Figure 4: Noa Matityahu's prototype in use by her grandmother

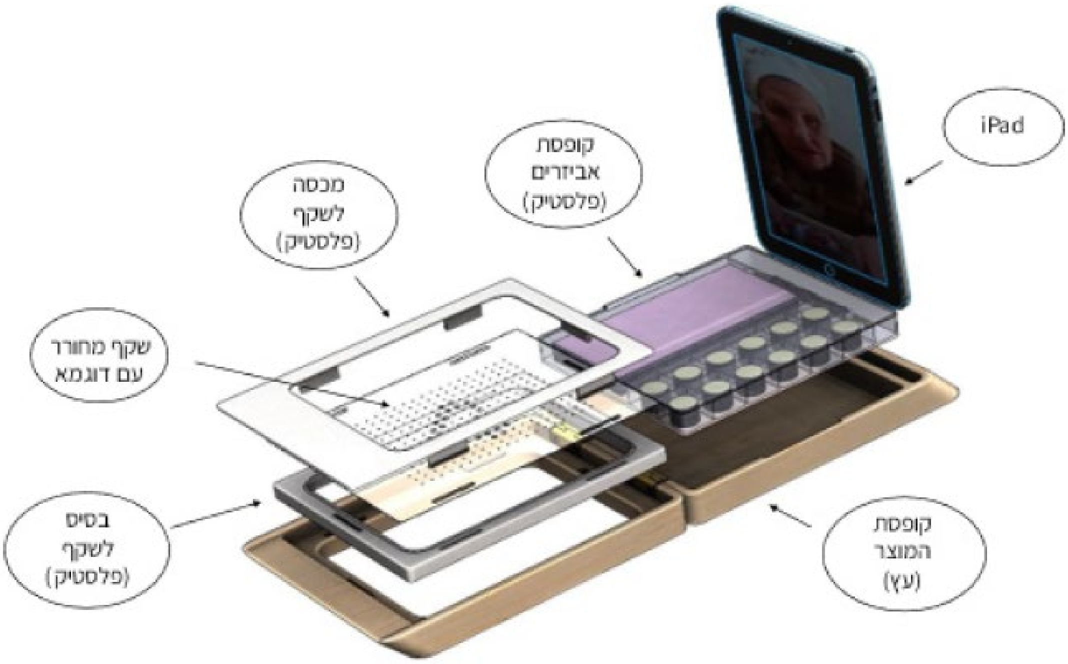


Figure 5: Noa Matityahu's detailed view of the prototype

Prototype as a Cultural Tool

In a different project, Hadar Sasson from HAC, focused on HIV among pregnant women in rural Uganda. Her unique project included two products – a testing platform meant for blood collecting and analysing samples, and a visual campaign meant for raising awareness – we wish to focus on the latter, due to its unique cultural attributes. For various reasons, including a post-COVID-19 climate and academic safety regulations, Sasson was unable to physically travel to Uganda to conduct research. However, she conducted multiple interviews and remote observations with both local community members and design practitioners from the research area. Indeed, for raising awareness Sasson designed a poster that evolved through several prototypes. While it was fairly clear that the layout needed an image, headline, and short text, and fonts were an easy choice, the image and colours presented various socio-cultural issues. Consulting a local graphic design studio, Sasson focused on a combination of harvest (corn) flowering through a mother, thus alluding to the importance of a healthy relationship between a mother and her foetus. The colours were gathered from local symbols and rituals and validated through the local graphic design studio as well. Indeed, in this case, the act of translation through the prototype did not only help to figure out design choices but also navigate and create a healthy dialogue between the two cultures – the designer and the local community.

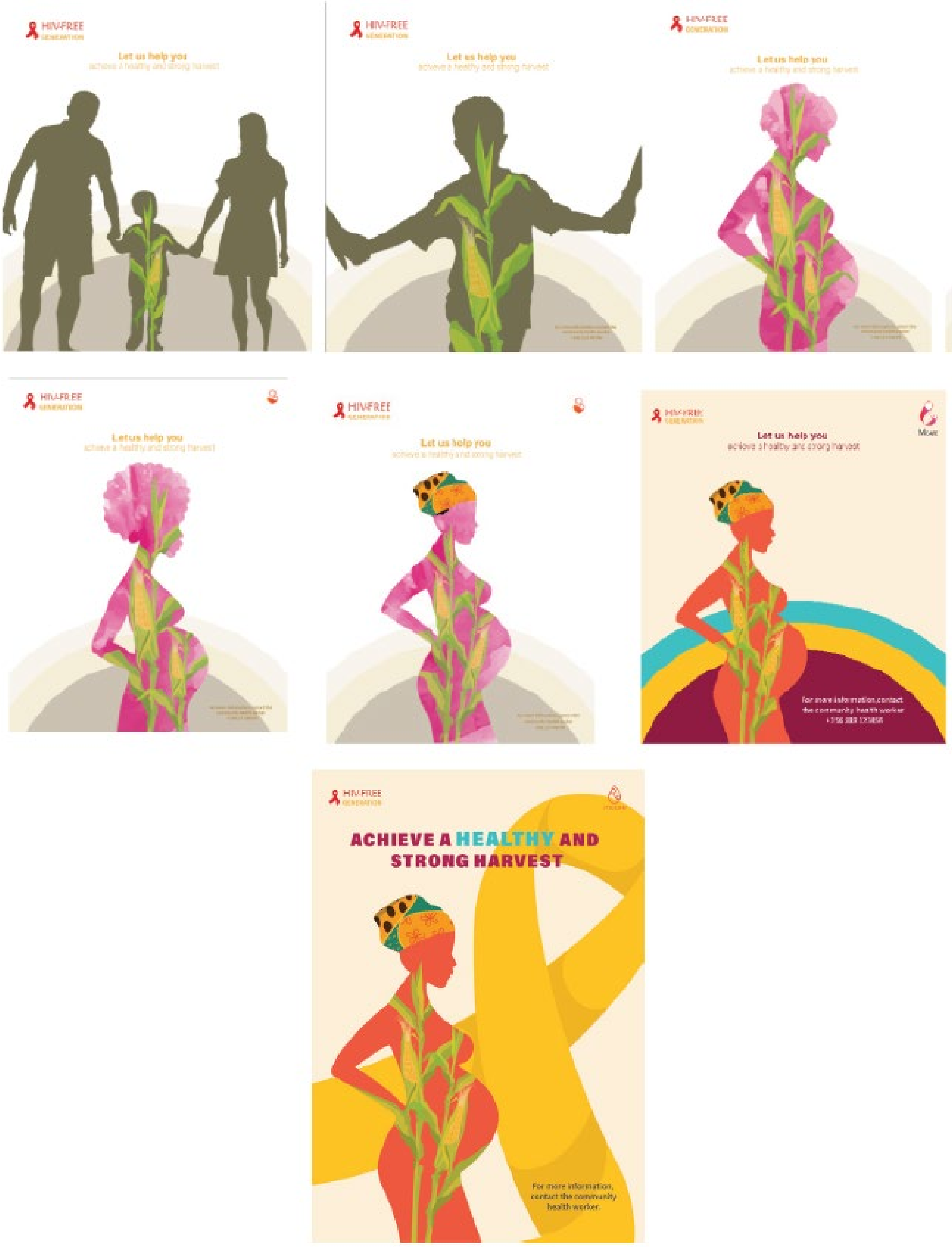


Figure 6: Hadar Sasson's poster prototypes for healthcare among rural communities in Uganda

Another case study from the same undergraduate program at HAC focused on a local community as well, that of ultra-orthodox Jewish women. In this community, it is strictly forbidden to mention the feminine body, even in relation to healthcare issues. Therefore, breast cancer, albeit being a crucial matter to confront from an early age, can lead to mothers choosing not to talk to their young daughters on the subject, and harming them while doing so. Designer Pliah Mendel chose to address this issue through design research. Her project consists of two elements - a board depicting three representations of lumps found in the feminine breast and their meaning in relation to breast cancer. These representations were made of silicone and were designed in a manner that would not imitate the feminine breast too closely to not induce shame or unease. In addition, these were hung on a wall in local Mikveh centres (a centre for ritualistic purification baths, taken a week after the end of menstruation). In this location, as women were naked in any case, a focus on their own bodies would not be considered boastful or generate shame. Thus, the prototype was used not only to help in the translation of the design concept, but also to decipher the amount of similitude between the prototype and an actual breast.

Figure 7: Pliah Mendel's prototype for breast cancer detection in the Ultra-Orthodox community in Jerusalem

Prototypes for/with a Neighborhood

Twiddle

Figure 8: Two uses of Twiddle

The first prototype is Twiddle, designed by Simon Barthmuss, Giulia Fasoli, and Vanessa Deotto, a deck chair, which is also a podium, but that can lend itself to other uses. It has been designed for a specific square of the neighbourhood Casanova-Kaiserau, Piazza Anita Pichler Platz, to allow people to attend, enliven and enjoy that location. It has been designed to be used for a special initiative – a local, not yet existing, festival – but it could be also used outside the context of the festival. Besides using it as a deck chair for public events related to the festival, anyone can turn it into a podium by easily flipping it. The three designers' main aim was to collect stories of the neighbourhood that could be told by each person who experienced and performed their narrative from Twiddle as a podium.

The project can also be seen as a service design, since these deck chairs/podiums can become a service available all year round and the designers also planned the service in order to become self-sustained, by outlining a system of care instigated the inhabitants. Conversely, Twiddle is an element of a much broader social design project which aims at making a specific square of the neighbourhood a place for social gathering and exchange.

The deck chair/podium is the centre and main mediator of such a project and its prototype is what emerges more clearly in the exhibit (Fig. 8), also because it is an artifact that could be used autonomously, not in relation to the neighbourhood and the festival for which it has been designed.

In another application, the prototype also stood at the centre of the final exam.

Such a project and its prototype emerged out of three months' worth of focused observation, walks, and familiarization with the neighbourhood, which made the designers particularly sensitive to squares "framed by the many large building complexes" (Fig. 9), as they described it . These activities were recorded mainly through photos and audio. The comparison of these recordings allowed the designers to identify busier and calmer places. The emptiness and stillness of squares and especially Anita Pichler's prompted the students to design something that would change such a situation. Therefore, they started to design directly on photos they took, turning them into grayscale.

Figure 9. Streets and buildings of the Casanova-Kaiserau neighborhood of Bozen-Bolzano.

Figure 10 Rendering of Twiddle use.

Visit walks and observations throughout the neighbourhood were translated into specific inscriptions (photos and audio). Each photo or audio track was then classified through an abstract category (busy/calm-still). From there, the idea of imbuing still places with life and activity was translated into drawings, where the uniformity of the still square was further highlighted by making it grayscale and by inserting in a contrasting way, coloured elements, which translated the previous abstract category "busy/calm" into another, less abstract one, coloured greyscale (Fig. 10).

The design of the deck chair/podium was then translated by materializing the "busy-coloured" part of the category, though somehow maintaining it given that used as a deck chair, Twiddle, affords more calmness, and used as a podium affords more activity and noise.

Figure 11. Twiddle at the final project exhibiton, where it could meet the inhabitants.

Rattopparole (word-patches)

Rattopparole (word-patches) is a project designed by Guillermo Mondelli and Andrea Righetto for the neighbourhood of Don Bosco in order to provide inhabitants with local pride and a sense of community. Rattopparole are patches designed from images and words related to the neighbourhood, that inhabitants can attach to their clothes to show their origin, and sense of belonging to their neighbourhood.

Figure 12. Patches designed and used in the Rattopparole project

Figure 13. Patch on a jacket.

The process of translation in this case is very explicit (Fig. 14). Through visits, walks, short interviews, and observations, words, colours and images of the quarters have been recorded and then stylized up to finally making them into prototype patches.

Figure 14. Translations from the neighborhood to the patches

The project has now been considered by the partner NGO, Officine Vispa, to be developed as part of its Social Tailoring, but since it has been developed during the first lockdown, prototypes need still to be used as a prompt for discussion with possible design partners.

Rivista Casanova

Figure 15. Rivista Casanova's prototype at the end of project exhibition

Figure 16. Rivista Casanova's prototype at the end of project exhibition with visitor

The last project from the first introductory semester of the Masters Degree in Eco-Social Design of the Free University of Bozen-Bolzano is *Rivista Casanova*, an "editorial" project of an oversized magazine ("rivista", in Italian), designed by Iske Conradie, Carola Kurz and Maria Pasqualini (Figg. 15 and 16), which entails, the display structure of such a magazine.

Rivista Casanova, was designed to be placed in the public space, tied and suspended to vertical elements present in the territory, like lampposts or trees. Therefore, it would act as a sort of paginated *dazibao* (wall newspaper). It was meant to allow participatory contributions from the inhabitants of the Casanova-Kaiserau neighborhood while relying on easily produced A4 sheets – used as basic module.

Like the other two design projects presented earlier, *Rivista Casanova* translated a field research activity into a product. The three students had noticed that there were no posters, no community boards, no graffiti or personalization, and no sense of shared lives within the neighborhood. The only stories being told about the inhabitants was from outside, from news outlets based outside the neighborhood, which often stigmatized the inhabitants of Casanova-Kaiserau. Therefore, the three students thought to provide an oversized magazine layout and structure which would generate curiosity and could work as point of attraction for the community around which gather and, at the same time, take directly part to the narration of the very neighborhood.

This case is of particular interest because it has been chosen by the Municipality of Bozen-Bolzano to be manufactured and installed in the neighborhood, therefore bringing the design project beyond the borders of a student design project and the prototype through which it is materialized. One consequence of this further step has been a second act of translation in which the prototype was transformed into an real-world product. Such further translation has entailed several significant transformations from the initial design prototype stemming mainly from legal issues relating to municipal legislation, especially related to safety and to the occupation of public space with permanent elements.

Because of these legal issue the main transformation from the first prototype is that the final product had to be manufactured with fixed pages and on wheels as a moveable element brought every morning to the defined location, rather than as an inherent and permanent “outgrowth” of the environment.

Moreover, the fact of being moveable entailed another transformation, not of the product, of the structure, but of it’s management– someone had to be in charge to move it in the public space during the day and removing it during the night. In part, this could be allocated to a community member, thus enhancing responsibility and involvement by other design partners.

As in the other cases presented in this paper, *Rivista Casanova* was not just a product – a display construct and a graphic layout – but rather a service, which required not only an act of design but also the periodical management of the creation of its content. While originally sketched, it remained mainly in the original design and prototype, and later assigned to the community in a co-design effort striving for the best management and display of content. However, this part has remained preliminary and unresolved and, once decided to actually manufacture the product, such aspect was overlooked, focusing on the materiality of the prototype and its interaction with the environment and expecting that someone would take care of the rest (the involved NGO? the three designers? the Municipality?). The actual production of the prototype, then, clarified the necessity of roles, responsibilities and timeframe of this project in the immediate future.

Thus, in this case the prototype’ strength shifted from the classic perception of a designed product (aesthetics, configuration, materials, colors etc.), to an ability to highlight a societal system, allocate responsibilities and harness a community to join in action. This is why, at present, the realization of the project has failed. It already started to show cracks during the manufacturing process, which entailed further work by the three student designers who probably did not expect this development and were not able or interested in following it’s further development. Indeed, while good for the community, in design education prototypes can highlight the nitty-gritty daily routine of functioning as a designer, as well as highlight the complexity of social projects contrary to classical project relying on a clear market and consumption trajectories.

Figure 17. Rivista Casanova's steel display

Figure 17. Rivista Casanova's steel display in the neighborhood

Discussion

The prototypes portrayed within the various design projects we have introduced in this paper stem from different standpoints in social design education trajectories – masters and bachelor, starting or ending of programs – and thus present differing complexities. Nevertheless, being all related to social design they all present key similarities, in that they encompass a phase of field research – whether the research field is own bodies in their socio-cultural complexities or a neighborhood or various kind of practices –, within which social research methods are used. From such field research elements, features and issues emerge – like body sensations, functional responses for values and attributes, color palettes, adequate shapes and sizes, etc. – that need to be then translated into the prototype, in order for it to work as a way to engage partners and stakeholders, as well as to flesh out social sensibilities and points of friction. Moreover, not only are they built around strong and defined social values and ideologies, but they are centered around specified local communities, with which designers work in-tandem.

Nevertheless, the prototypes developed at the end of the education trajectory tend to be used more easily as actual operational prototypes. Being in direct contact with local communities, this leads to using prototypes as material and visual liaison venues with community-based design partners (local residents), stakeholders and hypothetical clients and purchasers (NGOs, municipalities, local government agencies, industry partners etc.).

An important aspect of the ways in which prototypes are used within social design educational projects is the different functions they play within the project: First, validating the project's practical hypothesis ("is it working?"); second, applying theoretical knowledge gathered *through* and *with* and community ("does it generate relevant ideas, thoughts, and reflection?"); third, is the community engaged in and accepts the project through collaborative efforts ("is it socially and culturally appropriate?"); fourth, are the core values of the project truly embedded in the final designed product ("value-oriented correlation?").

Because of these various functions, there is an interesting reframing of the relationship between the design process, on the one hand, and the function and importance of the prototype in social design education, on the other. While in social design, prototypes tend to be less accurate in their material and industry-ready features, due to the complex and lengthy nature of these projects, their importance to the design process cannot be ignored. We can clearly see the tension between a working socially designed artefact and a working product in the last presented case study – the oversized community magazine. There, the final product, though working as an actual designed product, differed relevantly from the social design prototype, and did not work as well as a social design intervention.

All these raise an issue regarding the very notion of the adequate prototype for social design projects and how it should be harnessed in educational projects that are limited in time and resources, yet call for intricate answers to complex questions. Nevertheless, what these examples ascertain is that prototypes have a place and an important role to play in the designing process and more so when dealing with social design education. Indeed, as wicked problems become more numerous and designers are called to offer suitable solutions, so will the importance of using prototypes in think tanks and in relation to theoretical and complex models rise.

Seen as a combined act of translation and concretization, the prototype in social design continues to another layer. Through a gradual and collaborative process, it brings together an abstract layer (comprised of ideas, values, theories and concepts) as well as an empirical layer (comprised of data that was discovered, developed and put on trial through the design process) which evolve to a visual and material manifestation. These various instances – like a color palette, a material sample, a set of core values, and translation, into a specific configuration – emerge within the designing process and are then scattered along its development. The prototype is also made from the collection, selection and connection into an operational whole of these often very concrete elements. Thus, the act of translation serves not only to initiate these layers but also to mediate between the various design partners and finally gather these options and infuse them into a validated and interpreted designed whole.

Acknowledgments

The present paper is a collaborative effort by the two authors. If, however, for academic reasons individual responsibility is to be assigned, Alvise Mattozzi wrote the following sections: "Introduction", "Translation within Design", "Prototypes as translation from many to one"; "Prototypes for/with a Neighborhood"; Jonathan Ventura wrote the following sections: "Prototypes as special translations within the designing process", "Prototypes as translation in design education", "Prototypes' relevance for social design", "Prototype as Self-Enactment", "Prototype as Function Testing", "Prototype as a Cultural Tool", "Discussion".

References

Armando, A., & Durbiano, G. (2017). Teoria del progetto architettonico. Dai disegni agli effetti*. Roma: Carocci.*

Beaubois, V. (2015). Ethnographies du design. Vers une diagrammatisation de la conception*. Techniques & Culture. Revue semestrielle d'anthropologie des techniques, 64, 48–63.*

Corsín Jiménez, A. (2014). Introduction*. Journal of Cultural Economy, 7(4), 381–398.*

Gibson, R. (2020). The Corseted Skeleton: A Bioarchaeology of Binding*. Springer Nature.*

Hurkxkens, I. (2020). Robotic Landscapes: Topological Approaches to Terrain, Design, and Fabrication*. Unpublished doctoral dissertation, ETH Zurich University.*

Marcus, G. (2014). Prototyping and Contemporary Anthropological Experiments With Ethnographic Method*. Journal of Cultural Economy, 7(4), 399–410.*

Mattozzi, A. (2020). Describing Artifacts. What design and anthropology share, but Design Anthropology disregards*. Antropologia, 7(2 N.S.), 105–128.*

Parolin, L.L., & Mattozzi A. (2013). Sensitive Translations: Sensitive Dimension and Knowledge within Two Craftsmen's Workplaces. *Scandinavian Journal of Management*, 29 (4): 353–66..

Sanders, E. B.-N., & Stappers, P. J. (2014). Probes, toolkits and prototypes: Three approaches to making in codesigning*. CoDesign, 10(1), 5–14.*

Stappers, P. J. (2007). Doing Design as a Part of Doing Research*. In R. Michel (Ed.), Design Research Now: Essays and Selected Projects (pp. 81–91). Birkhäuser.*

Ventura, J., & Ventura, G. (2015) Exphrasis : Verbalizing Unexisting Objects in the World of Design*. Design and Culture 7 (April): 185–202.*

Alvise Mattozzi

Alvise Mattozzi, sociologist, is, since one year, Assistant Professor of Social Studies of Science and Technology at DIATI (Department of Environment, Land and Infrastructure Engineering) of the Politecnico di Torino (Italy), where he is also a member of the Interdepartmental Research Center TheSeUs – Technology, Society, Humanity. Before, he has worked for 11 years at the Faculty of Design of the Free University of Bolzano. There, he has contributed to create the Master in Eco-Social Design, in which he taught Social Studies of Design.
His research unfolds between the fields of Science and Technolgy Studies and Design Studies, investigating the social role of artifacts and designing practices, through empirical qualitative researches.
He is a founding member of the Social Design Network.

Jonathan Ventura

Prof. Jonathan Ventura is a design anthropologist specializing in social and healthcare design, design research and design theories. Ventura completed his PhD in applied design anthropology in a joint program of the department of sociology and anthropology at the Hebrew University of Jerusalem and the department of industrial design at Bezalel Academy of Art and Design in Jerusalem. Jonathan continued to complete a post-doctorate in social design at the Helen Hamlyn Centre for Design at the Royal College of Art in London UK.
Currently, Ventura is the Director of The Unit for History and Philosophy of Art, Design and Technology at Shenkar: Engineering. Design. Art., and an associate professor at the department of inclusive design at Hadassah Academic College in Jerusalem. Ventura is also the co-director of the international Social Design Network (socialdesignnetwork.org). Ventura specializes in applied design anthropology, social design and the meeting points between theory, research, and practice, both in historic and theoretic layers. His latest publications include various articles and papers including 18 entries in the *Bloomsbury Design Library*, and for the book *Introduction to Design Theory* published by Routledge in 2023.

Prototyping of theories

Sisse Schaldemose, VIA University College, Aarhus, Denmark

Abstract

This paper explores the prospects of prototyping as an aid in understanding theory among students at a higher education. Drawing on research by Buur et.al. (2022) into Design Anthropological Theory Instruments, this research, brings the concept of theory instruments into a teaching setting among social work students. Using research through design (Zimmerman, Stolterman & Forlizzi, 2010), this research explores how working with tangible materials influence students' understanding of theory.
Prototyping theories can help bridge the gap between abstract concepts and concrete application. The research is concerned with the tangibility of abstract theory and explores both the process of making prototypes as well as the impact of more finished theory instruments. Introducing theory instruments or having the students physicalizing a theory does not automatically lead to a deeper or more thorough understanding of theory and does not prevent misconceptions or simplifications. However, the tangible nature of the process opens for a reflexive conversation. The physical models becomes drivers for the discussion about the theory and what is essential or important in the theory, and as such the prototypes can be perceived as "boundary objects" (Star & Griesemer, 1989) or "shared objects of thoughts" (Kirch, 2010). The research also finds that purely visual representations sometimes hinder fully grasping the complexity of a theory and when the theory is physicalized, it opens for further exploration and conversations about the complexity of a theory as it becomes tangible. By physicalizing theory, it becomes clearer to the students that a model has its limitations and cannot capture all aspects of a theory and thus strengthening the student's metamodeling competencies (Schwartz & White, 2005).

Physicalizing, Keyword 2; objects vs. things, Keyword 3: metamodeling, Keyword 4: theory-praxis

Houde and Hill (1997) defines prototype as "*any representation of a design idea, regardless of medium. This includes a preexisting object when used to answer a design question* (Houde & Hill, 1997). Prototypes are commonly used to explore or demonstrate some aspect of a future artefact. "*An artifact may be a commercially released product or any end-result of a design activity such as a concept system developed for research purposes"* (Houde & Hill, 1997). This paper seeks to illuminate that prototypes also can be used in the proces of understanding theory. Using things or tangibles as part of the design process is well known within the design community (Brandt & Grunnet, 2000, Buur & Mitchell, 2010, Brandt, 2007, Stappers & Sanders, 2004, Sanders & Stappers, 2014). Mitchell and Buur states that *"The value of such props or "things to think with" are determined not by their realism or fidelity but by the dialogue the objects help to facilitate and by the inspirations that they spark"* (Mitchell & Buur, 2010, p.30). The fidelity or realism is not at the essence but rather the possibility for dialogue that these props create. In teaching, tangibles or physical learning objects (sometimes referred to as manipulatives) are primarily designed for younger learners (Schneider, 2017). The reason being the assumption that adults can skip the concrete stage and jump directly to a more abstract representation and that manipulatives often are static thus limiting their representation value of more advanced concepts.

The social work profession is both an academic discipline as well as a practice-based profession. For a social work student as well as a certified social worker, theories are often means to understand a very complex social world. Theories are for that reason most valuable when they are applied to understand or comprehend the many complex social problems encountered by social workers. To apply a theory, it is necessary to be able to fully understand it. This research seeks to bring the insight from the design world into teaching. Teaching is to a large part a matter of facilitating the best possible learning environment. Eva Brandt finds that the use of mock-ups *"served as boundary objects that spanned the gap between the different competencies and interests of participants in design."* (Brandt, 2007, p.1). If the models made by the students are perceived as mock-ups (they are physical representations of an idea or concept) they might also serve as boundary objects that can span the gap between not only the student's different understandings but also the gap between theory and praxis.

Social work students are used to seeing visual 2D representations of theory as part of their education. These are often in the form of diagrams, graphs, tables and charts etc. What is common for these illustrations is that they are all what could be described as 'objects' in Tim Ingold's words. Tim Ingold insists on a radical distinction between objects and things (Ingold, 2010, 2012). Drawing on Heidegger's essay "the thing" he states: *"the object stands before us as a fait accompli, presenting its congealed, outer surfaces to our inspection. The thing, by contrast, is a 'going on', or better, a place where several goings on become entwined."* (Ingold, 2010, p.4). Perceiving the visual illustrations, which the students are usually presented with, as objects means that they might be perceived as a final finished representation and as such "the truth". Ingold quotes the painter Paul Klee who insisted, that giving rise to forms is more important than the forms themselves. *"Form is the end, death', he wrote. 'Form-giving is movement, action. Form-giving is life"* (2010, p.2). What this paper seeks to explore is whether prototyping can be perceived as a form-giving process and as such bring life to the students' understanding and comprehension of theory. This paper stipulates that the prototyping of theory can aid the social work students in the process of comprehending sometimes very complex theories.

Methodology

The constructivist and social constructivist learning theories inspire the research for this paper. Constructivist learning-theory (primarily attributed to Jean Piaget) builds on the foundation that learning is an active process between the individual and their surroundings (Dolin, 2015 & Ulriksen, 2016). A key element within this approach is that all new knowledge is implemented, shaped, and incorporated into the existing knowledge. This is an important notion, as the student isn't an empty vessel that is just waiting to be filled but the information needs to be reconfigured into existing knowledge.

The social constructivist learning theory is predominately influenced by Lev Vygotsky and builds on the notion that any learning is socially constructed rather than an individual process and that learning takes place in a social relation between the surroundings, the culture one is a part of and the artefacts one encounters and other people one is in interaction with. In both understandings, the fundamental notion is that learning is an active process. For learning to happen, the learner needs to be part of the process (Ulriksen, 2016). As the focus of this research is an inquiry into how working with tangible materials influence students understanding and perception of theory, and with the above learning- theory in mind a qualitative approach in the form of collaborative workshops were chosen. The main focus has been the student's experiences rather than any kind of causality between tangible materials and learning.

In total six workshops were held, each lasting two hours in the spring of 2021. Four workshops with students and two workshops with teachers from the social work education. The focus of the two first workshops was for students to make physical representations of theory they knew. At their disposal were clay, pipe cleaners, pompoms, toilet paper rolls, glue, string, and rubber bands. Pen, paper and any other drawing devices were deliberately left out, in an aim to shift their attention away from a visual 2-dimensional representation and challenge them to think in a 3-dimensional way about the theories, as the focus was to investigate what a tangible 3-dimensional representation would do to the perception of theory. The two workshops with the teachers focused on the development of two theory instruments (Buur et.al, 2022) and the final two workshops with students focused on testing those theory instruments.

The impact of materials

Throughout the two first workshops, the significance of the material available for the students came to prove quite important. The material available in the workshops seemed to influence not just the students final models but also the building process and as such their perception of theory. The models made in the first workshop were nearly all flat (almost 2D) some to the extent, that they might as well have been drawn by hand. Therefore, other materials were introduced in the second workshop (different shaped building blocks and Styrofoam balls). All the models made in the second workshop were all 3-dimensional. The material that was added was all included in the models and the common denominator for the materials is that they carry a resemblance or an inherent symbolic meaning. They look like something already known. A Styrofoam ball is round and can resemble a head, and then very quickly a person. A building block, shaped like a bridge, can easily be interpreted in the symbolic meaning of the word bridge – bringing something together, bridging, a pathway etc. One interpretation could be that it lowers the threshold for participating as the inherent symbolic meaning sparks the inspiration. Several of the students picked the building blocks that were shaped in

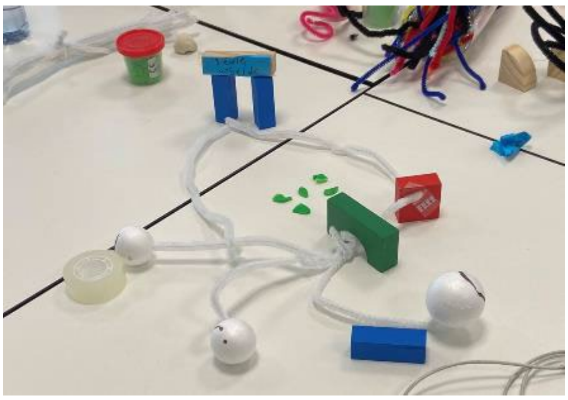


Figure 1: participant 4 and his model of social capital

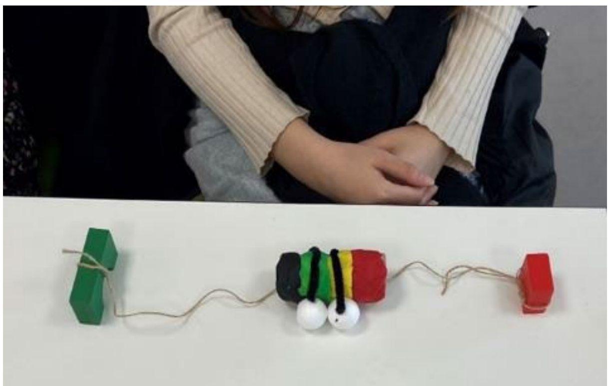


Figure 2: Participant 3 and her model of empowerment

a certain way, for instance, a bridge and turned that symbolic meaning into a symbolic meaning in the theory. For instance, one student used a brick shaped like a bridge to symbolise “bridging social capital” coined by Robert D. Putnam (1995) (Figure 1) and another student used a similar brick to symbolize achievement of empowerment (Figure 2).

According to Donald Schön (1992), different designers often select different materials when presented with the same stock of available materials, and even appreciate the ‘same’ objects in different ways and ascribe different meanings and features to them. In his paper “*Designing as reflective conversation with the materials of a design situation*” (1992), Schön reflects upon this variation in preference and its implication and states:

“*Because each of them saw the materials in a different way, chose to use different items, singled out different features, and exploited different relationships between items and features, each student constructed a unique design world*.” (Schön, 1992).

However, what guides the students into picking specific materials in this research and ascribing certain meanings to them might also be seen as what Donald Norman calls ‘signifiers’ (2008). The building blocks can be viewed as such signifiers, firstly because some of them are shaped like for instance a bridge and as such offer interpretations either literately or metaphorically of bridging. The embedded clues or signs seem to fuel the imagination and as is seen from the examples, these signs are appropriated very differently. To some students it seems like these signifiers offer help in the modelling process. Going from very abstract theory to a very concrete representation in the shape of a model might prove easier, with materials that have some kind of embedded ques that can spark the imagination. Particularly with students to whom such “creative activities” are quite foreign.

The impact of sensorimotor coupling

Another striking found in the research is how the model making challenge the students cognitive process and their perception of theory. Several of the students expressed that they found the process difficult but also exciting *“I thought it was incredibly exciting to be part of. I thought it was **difficult** at first to model a theory by hand. Because you really must think **differently** and **creatively”*** (Workshop 1, participant 1).

It was clear from both the statements but also the non-verbal communication, that the students were highly focused and concentrated, while making the models. Despite it being, an extracurricular activity, they all seemed deeply consumed and focused in the task. This is in line with the constructivist perception of learning. The students are invited to take actively part in the learning process and are not just passive perceivers of information, which might prove significantly more challenging than just reading about it or listen to a lecture.

Even though the students are using their hands, they highlight the brain activity involved:

*“To me it’s **candy for the brain**. Sitting here, being creative, working with my hands it’s focus training. I haven’t gone into this thinking ‘I’m just going to make the most dope thing’ but more with the approach that now I’m going to **work with my brain**”* (Workshop 2, participant 2).

*“Yeah, it’s true that it is **good for the brain** because you force yourself to think in a **completely different way**. You don’t think about the time because you are so consumed*

within theory (Workshop 2, participant 5).

The students highlights the cognitive process which of cause, has to do with the task of modelling *theory*, but it might also be an example of what Schön would call a reflective conversation with the design situation (Schön, 1992) and in line with sensorimotor coupling (Dijk, 2013). The students are in a sense in dialogue with their model; they are not just simply creating a model through a predefined sketch in their head, but instead in parallel and in conversation with the material. This is seen several times during the first two workshops where the students are picking up materials, feeling, bending, putting it back again, picking up another material and thinking aloud saying things like "I'm just thinking of the best way…" or "I think it should be green – or maybe blue..”or "I'm wondering how to approach it". I don't see any indications of the materials being used as a relief of cognitive load as suggested by the extended mind theory (Clark & Chalmers, 1998) as none of the participants expressed any kind of cognitive relief but quite the opposite. The students all describe the process as difficult yet exiting. It seems more like a dialectic process where the material provides feedback and informs the cognitive process. In order for the students to create a model that captures the essence of the theory, they need to understand the theory and the development of the model almost automatically becomes a back and forth process – trying out, changing, alternating, moving etc. In that process the students reflects about the theory to an extend that wouldn't be necessary, if they were simply just hearing or reading about it.

The impact of collaboration

After each of the students had made their model, they each presented it to each other which sparked a lot of discussion. It was through this discussion, their thoughts behind their models were revealed, and realisations became apparent. Such a realisation is presented in the following transcript from workshop 2. Participant 3 has just presented her model of empowerment and the following conversation takes place:

Participant 2 (referring to the model in Figure 2): *"How do you suppose one gets from there (pointing at the red building block) to there (pointing to the green building block)? Now it's just a 'picture' that shows 'this is the road you need to take' – but if the model should show how one gets to be empowered?*

In this comment, participant 2 is challenging participant 3's perception of empowerment and tries to indicate that something might be missing.

Participant 3: *"well I'm trying to illustrate that using this tunnel (pointing to middle part).That is also the reason there is this opening (pointing to the green building block that has a hole in it and looks like a bridge) to show that is where you have reached empowerment but how you get there, I haven't thought about".*

Participant 3 is now beginning to realise that there might be something in the theory she has overlooked and that the model might be too simplistic.

Participant 1 tries to suggest ways to improve the model to make it more in line with the theory:

Participant 1: "*I wonder; what if there were something that went the other way? Where you have the tunnel, maybe a ball that moved if something changed? Some event that had an impact, an influence that effected the process and then the ball would move closer to the green building block?"*

By making this comment I'm contemplating whether she is suggesting ways for the model to be less static: *"How could it be more interactive?"*

Participant 1: *"It is exactly a process. It's not linear"*

This comment leads participant 3 to realise that what the model lacks, is a way to show the complexity of the theory of empowerment:

Participant 3: *"Well that's true because right now we are sort of going from A to B (points to the model) but it isn't always like that. Well, most of the time it's not like that at all."*

This leads participant 2 to make the following comment: *"I can clearly see the visual aspect of it but how can we bring it to life? Because right now it's just something we can look at".*

This comment highlights the point of a physical model – if the model should contribute to something more than what a visual representation can do, it needs to add something more. In particular when it comes to quite complex theory. If not, it ends up simplifying the theory to an extend where the representation isn't a helpful aid.

Towards the end of the workshop participant 2 refers to the above episode reflecting about the process: *"Well just look, a completely "dead" model got brought to life just from us talking about it".*

Van Dijk states that *"Socially Situated Practice research emphasizes how artefacts 'get taken up' as meaningful elements within a social process between people."* (2013, p.44). In the above example we see just that. Meaning is created not just between the model and that one participant who have made it but also in a dynamic social process between the students in cooperation with the materials. The material at hand becomes drivers for the discussion about the theory and what is essential or important in the theory (that empowerment is not a linear process where one goes from A to B).

These models might be perceived as boundary objects. Susan Leigh Star and James R. Griesemer introduced the concept Boundary objects in 1989 and described them as "*objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individualsite use. These objects may be abstract or concrete. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation*." (Star & Griesemer, 1989).

Viewing these models created by the students as mock-ups they might serve as exactly such boundary objects. Eva Brandt describes how mock-ups serves as *"'boundary objects' that spanned the gap between the different competencies and interests of participants in design"* (Brandt, 2007).

The above model made by participant 3, might be perceived as such a boundary object or perhaps as what David Kirsch refers to as 'a shared object of thoughts' - an external representation or as an additional aid to the words. *"When someone externalizes a structure, they are communicating with themselves, as well as making it possible for others to share with them a common focus. An externalized structure can be shared as an object of thought..[]..A shared object of thought means that different thinkers share mechanisms of reference and for agreeing on attributes of the referent"* (Kirsch, 2010). Towards the end of workshop 2 one participant states: " *You just get it visualised in a completely different way*

Figure 3: participant 5, the ecological system theory

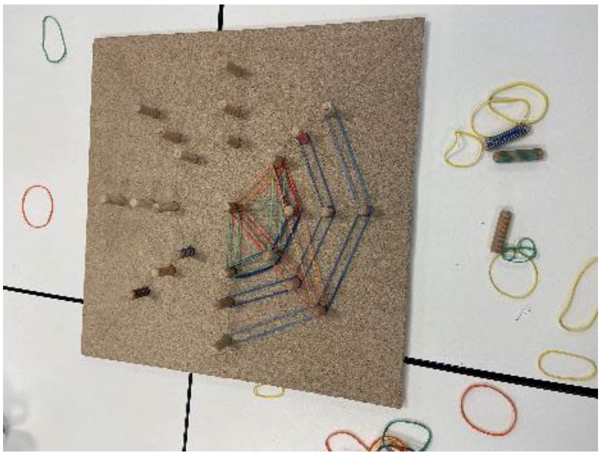


Figure 4: The theory instrument with the concentric circles “re-established”

than when you have ordinary teaching where you must make your own pictures in your head” (Workshop 2, participant 5). This underlines the value of psycial representations as they offer a externalised shared object of thoght that can be discussed and collaborativly elaborated. Instead of the students, trying to explain themselves purely verbally they now refer to the same externalised idea that is in front of them that can be elaborated or challenged. In line with Buur & Mitchell (2010), David Kirsch (2010) also highlights these externalised elements as vehicle for thoughts or “things to think with”. In the above example the model serves as just such a vehicle, as it aids the students in their conversation as they are now referring to the same parts of the model (the red building block as the beginning, the green the end and the process in the middle).

The impact of visual models

Representations (visual or physical) are created to lower the threshold for comprehension, especially with complex topics. As documented by Fuhrmann et.al. (2018) modelling promotes the understanding of complex scientific concepts and helps students overcome misconceptions. But what if it isn’t always the case? What if a representation or model does the exact opposite? What if the representation itself leads to misconceptions? Bronfenbrenner’s ecological systems theory (Bronfenbrenner,1979) is usually represented with concentric circles (Figure 5) in various ways though Bronfenbrenner himself never represented his theory this way but instead referred to Russian dolls as a metaphor. However, most students are familiar with the visual representation in the shape of the concentric circles and will often refer to exactly that model if asked to describe the theory.

In workshop 1, a student makes a physical representation of the model, and it is indeed made up of concentric circles (Figure 3).

As part of the two design workshops with the teachers, several prototypes of the Bronfenbrenner theory were created. It was found to be very difficult not to be affected by the visual representation and several of the attempts had many similarities with the visual representations (Figure 4).

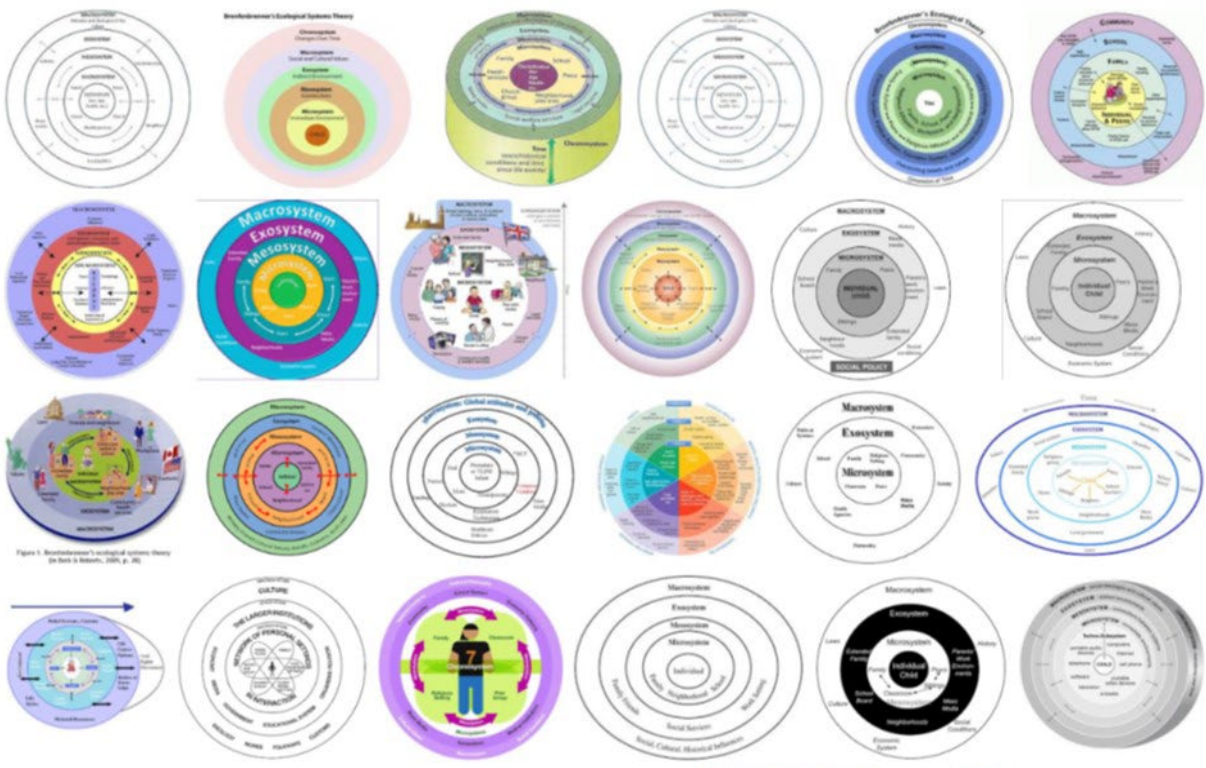


Figure 5: showing some of the visual models used to explain the ecological system theory (Shelton, 2017)

In workshop 4 were the prototype was presented, one student tries to re-establish the concentric circles with rubber bands on the board so that it resembled the visual representation even more (Figure 4). A way to understand this could be that the visual model has become a fait accompli and perhaps in Ingold's definition an object. Something that stands before us as complete and final and any further changes it may undergo belongs to the phase of use or consumption (Ingold, 2012). Understanding the visual representation of the ecological theory as an object has the implications that it is "finished" and maybe also to some extent that it is "true" and as such doesn't invite for any different interpretations but instead application or use. If the model instead in Ingold's words is viewed as a collection of materials or a thing it can be seen as *"a potential—for further making, growth, and transformation"* (Ingold, 2012). In a sense what needs to happen is a deconstruction of the object and a way to deconstruct the model is to physicalize it. This is to some extent seen in workshop 1 when the student (participant 5) makes a physical representation of the ecological system theory. She does reach some new insights she might not have achieved only by looking at the model. Some of it partly because she can now rearrange the circles. This might relate to what Kirsch (2010) calls 'the power of rearrangement'. The possibility to manipulate and rearrange something and not just look at it offers different ways of synthesising and connecting parts in a new way that a visual representation doesn't offer. To some extent, the visual representation is "dead" as it isn't a "becoming" whereas a physical representation can invite for transformation and further making provided it holds sufficient encouragement for manipulation. When students are at the beginning of grasping a theory like Bronfenbrenner's, they might heavily rely on simplistic models and overlook that a model cannot capture all aspects of a theory. When students model their own or when presented with a prototype in the form of a theory instrument they get confronted with this dilemma or at least some of them start to reflect upon that.

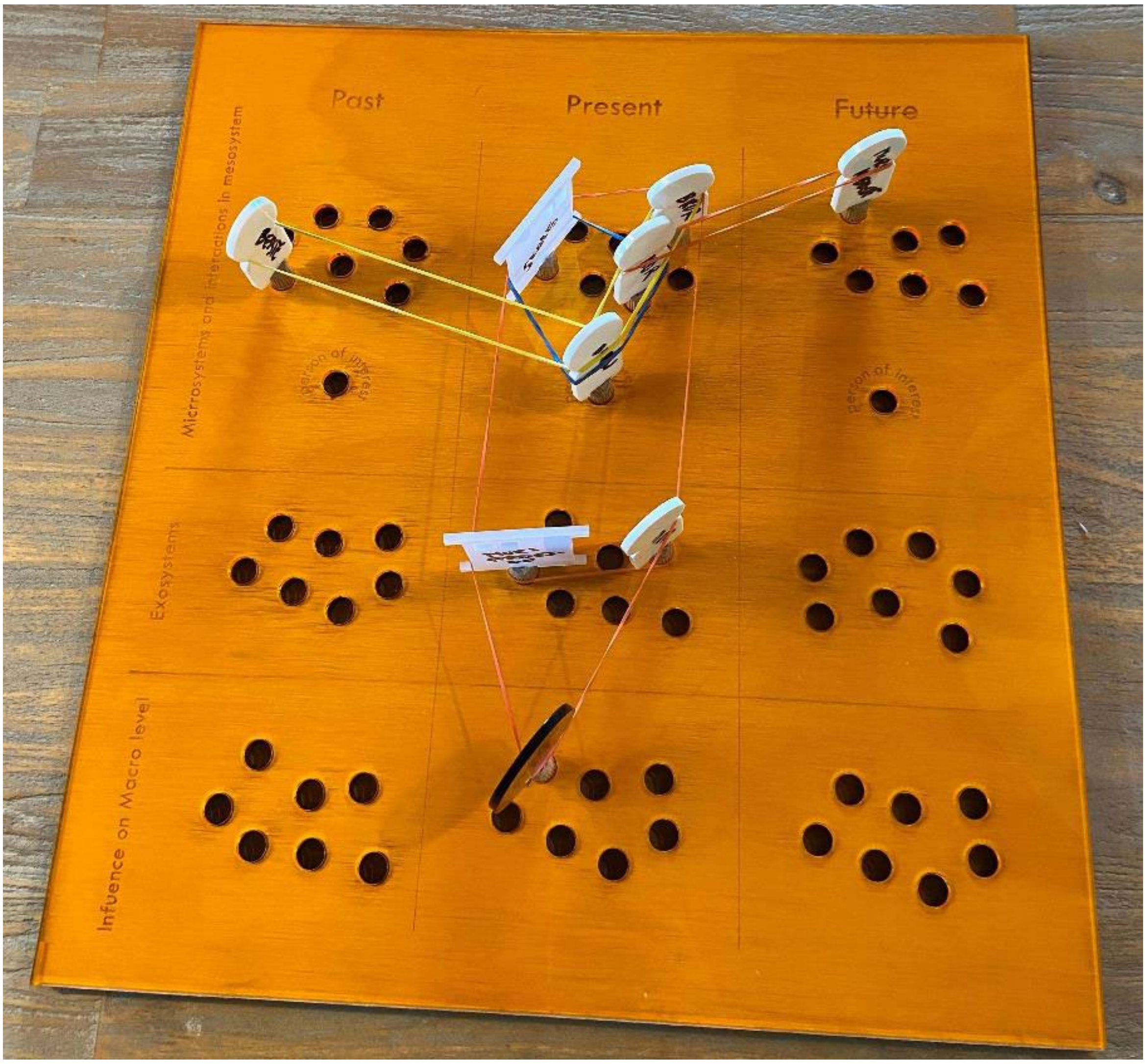


Figure 6: the latest prototype of the ecological system theory

Discussion

The motivation for this research has been to explore what theory Instruments (Buur et.al. 2022) and the proces of prototyping could offer social work students in their pursuit to understand and grasp theory. It is common in most educations to ascribe to a learning taxonomy in order to assess the students' learning outcomes and for the social work education, the Biggs Structure of Learning outcomes (SOLO) taxonomy has been selected (Biggs, 2012).

Based on this research the question now arises: does tangible teaching help stimulate reflection and thus support higher learning outcomes? From the two first workshops, it is evident the starting point for the students were very different. Some seemed to be able to critique and juggle different concepts thus indicating a quite high abstraction level to begin with. This is forinstance seen when two students creates a physical representation of Goffmans theory of frontstage/backstage (Figure 8). Others were grasping to comprehend the theory they had chosen and therefore it comes across as quite simple and with Biggs

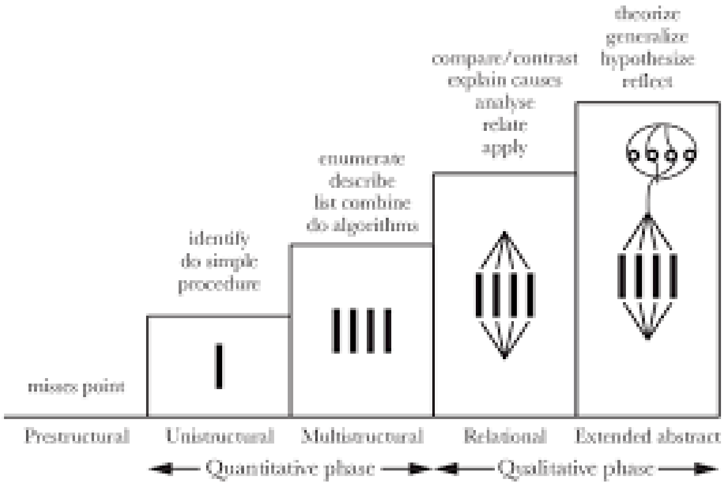


Figure7 – Solo taxonomy (Biggs & Tang, 2011, p. 91)

words “unistructural” (Biggs, 2012). This is for instance seen in Figure 9, which is a physical representaion of Honneths recognition theory. In one instance, the model is even what could be called pre-structural where a student has gotten two theories mixed up (Bourdieu and Putnam – Figure 1). This means that introducing theory modelling to the students is no magic wand and doesn’t prevent reproducing misconceptions. However, what is also seen in the workshops, is that even when the models are produced on a quite unistructural level they serve as a starting point for further exploration and that misconceptions are corrected by the other students. It needs to be stated, that none of the students had prepared for the workshop for instance by reading papers etc. beforehand, as the threshold for participating deliberately was kept to a minimum. They therefore relied on their memory of the theories. Using prototyping as an active part of teaching would require a different approach and would probably rely on the students being prepared for instance by reading a particular theory beforehand. Prototyping seem to aid student-centred learning and more active involvement of the students which might lead to higher learning outcomes (Hoidn & Klemenčič, 2020). That however will need further research to explore. The process of prototyping might make it less intimidating for students to receive feedback from their peers as there may well be an

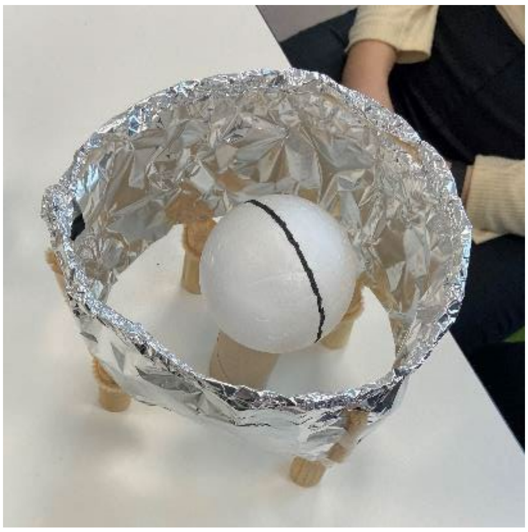


Figure 8: Goffman, Frontstage/Backstage

Figure 9: Honneth theory of recognition

acceptance of the imperfection of the model due to the materials at hand and the unfamiliarity of the exercise. The imperfections of the prototypes also seem to invite for interpretation and dialogue to a wider extent than what would be the case with a drawing or a written paper where more precision might be expected.

Conclusion

Through this research, it is found that in the process of making a model the students are in dialogue with their model. They are not just simply creating a model through a predefined sketch in their head, but instead in parallel and in conversation with the material (Schön, 1992, Van Dijk, 2013) as the material provides feedback and informs the cognitive process. The power of this conversation with the material is found to be particularly predominant when it is done collaboratively. The material at hand becomes drivers for the discussion about the theory and what is essential or important in the theory, and as such the model can be perceived as a boundary object (Star & Griesemer, 1989) or “a shared object of thoughts” (Kirch, 2010). Even when the models are produced on a quite unistructural level (Biggs, 2012), they serve as a starting point for further exploration and the other students corrects misconceptions. In this research, it is found that visual representations sometimes can stand in the way of fully grasping the complexity of a theory. This is exemplified by Bronfenbrenner’s ecological systems theory (Bronfenbrenner, 1979). All representations are simplifications and leave aspects of a theory out, but when a representation is visual there is a risk that the representation gets taken for granted due to the static nature that doesn’t leave room for further manipulation. However, when the theory is physicalized, it opens for further exploration and conversations about the complexity of the theory. By deconstructing the visual model and making another by physicalizing it, it is made clear that a model has its limitations and can’t capture all aspects of a theory. The possibility to manipulate and rearrange something and not just look at it offers different ways of synthesising and connecting parts in a new way that a visual representation doesn’t offer. Introducing theory instruments or having the students physicalizing a theory doesn’t automatically lead to a deeper or more thorough understanding of theory and doesn’t prevent misconceptions or simplifications. It is however found that the tangible nature of the process opens for a reflexive conversation that gives access to the misconceptions as they might else just have stayed in the head.

References

Biggs, J. & Tang, C. (2011). Teaching for quality Learning at University. What the student does. (4th ed). Open University Press. New York

Biggs, J. (2012) What the student does: teaching for enhanced learning, Higher Education Research & Development, 31:1, 39-55, DOI:10.1080/07294360.2012.642839

Brandt, E. and Grunnet, C. (2000). Evoking the future: Drama and props in user centered design. Proceedings of Participatory Design Conference, 11–20.

Brinkmann, S. (2012). Qualitive Inquiry in Everyday Life. Working with Everyday Life Materials. Sage Publications Ltd.

Bronfenbrenner, U. (1979). The ecology of human development – experiments by nature and design. Harvard University Press

Buur, J. and Mitchell, R. (2010). Tangible business model sketches to support participatory design. Desire '10: proceedings of the 1st Desire Network Conference on Creativity and Innovation in Design. 29-33

Buur, J. and Mitchell, R. (2010). Tangible business model sketches to support participatory design. Desire '10: proceedings of the 1st Desire Network Conference on Creativity and Innovation in Design. 29-33

Buur, J., Kjærsgaard, M.G., Sorensen, J. & Ötzke (2022). Studying Interaction Design Practices with Theory Instruments. DRS 2022, Bilbao

Clark, A. & Chalmers, D. (1998) The Extended Mind, Analysis, Volume 58, Issue 1, January 1998, Pages 7–19, https://doi.org/10.1093/analys/58.1.7

Collins, C. S., & Stockton, C. M. (2018). The Central Role of Theory in Qualitative Research. International Journal of Qualitative Methods. https://doi. org/10.1177/1609406918797475

De Michelis, G. (2017). What design tells us about objects and things. In L. Atzmon & P. Boradkar (Ed.). Encountering Things: Design and Theories of Things (pp. 123–132). London: Bloomsbury Academic. Retrieved April 1, 2022, from http://dx.doi. org/10.5040/9781474293839.ch-009

Dijk, J. V. (2013). Creating traces, sharing insight: Explorations in embodied cognition design. Technische Universiteit Eindhoven. https://doi.org/10.6100/IR759609

Dolin, J. (2015). Undervisning for læring. In: L. Rienecker, P. Stray Jørgensen, J. Dolin & G. Holten Ingerslev (edt). Universistetspædagogik (p.65-91).

Fuhrmann, T., Schneider, B., & Blikstein, P. (2018) Should students design or interact with models? Using the Bifocal Modelling Framework to investigate model construction in high school science, International Journal of Science Education, 40:8,867-893, DOI: 10.1080/09500693.2018.1453175

Hoidn, S. & Klemenčič, M. (2020). The Routledge International Handbook of Student-Centered Learning and Teaching in Higher Education. Routledge, London, Abingdon, Oxon.

Houde, S., and Hill, C., What Do Prototypes Prototype?, in Handbook of Human-Computer Interaction (2nd Ed.), M. Helander, T.␣ Landauer, and P. Prabhu (eds.): Elsevier Science B. V: Amsterdam, 1997

Ingold, T. (2010). Bringing things to life: Creative entanglements in a world of materials (Vol. 15, pp. 1-14).

Ingold, T. (2012). Toward an ecology of materials. Annual Review of Anthropology 2012 41:1, 427-442

Kirsh, D. (2010). Thinking with External Representations. DOI:10.1007/978-3-319-49115-8_4

Norman, D. A. (2008). The way I see IT signifiers, not affordances. interactions, 15(6), 18-19.

Putnam, R.D. (1995). Bowling Alone: America's Declining Social Capital. Journal of Democracy 6(1), 65-78. doi:10.1353/jod.1995.0002

Sanders, E.B.N. & Stappers, P.J. (2014). Probes, toolkits and prototypes: three approaches to making in codesigning, CoDesign, 10:1, 5-14, DOI: 10.1080/15710882.2014.888183

Schwarz, C. & White, B.Y. (2005). Metamodeling Knowledge: Developing Students' Understanding of Scientific Modeling. Cognition and Instruction. 23. 10.1207/ s1532690xci2302_1.

Schön, D.A. (1992) Designing as reflective conversation with the materials of a design situation. Research in Engineering Design 3, 131–147. https://doi.org/10.1007/ BF01580516

Shelton, L.G. (2017). Graphic representations of Bronfenbrenner's ecological systems framework. The university of Vermont

Stappers, P.J., & Sanders, E. (2004). Generative tools for context mapping: tuning the tools. In D. Mcdonagh, P. Hekkert, J. Van Erp & D. Gyi (Ed.). Design and emotion (pp. 77–81). Taylor & Francis Inc.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social studies of science, 19(3), 387-420.

Ulriksen, L. (2016). God undervisning på de videregående uddannelser. En forskningsbaseret brugsbog. Frydenlund.

Zimmerman, J. Stolterman, E. & Forlizzi, J. (2010). An analysis and critique of Research through Design: towards a formalization of a research approach. In Proceedings of the 8th ACM Conference on Designing Interactive Systems (DIS '10). Association for Computing Machinery, New York, NY, USA, 310–319. https://doi. org/10.1145/1858171.1858228

Sisse Schaldemose

Associate professor at the social work department at VIA University College Aarhus. MSc in IT product Design, BA in social work. Researcher at the Research Centre for Innovation and Entrepreneurship (CIE) VIA in the research programme for social innovation. Currently enrolled in the research programme "room for practice" investigating how to minimise the theory-practice gap through a co-creative process with various professionals from the field.

Role of Physical mock-ups in the Ideation phase: A thematic analysis of the Pedagogic approach

Subramanya T N, IIT Bombay, India
Dr. Chakravarthy B K, IIT Bombay, India
Dr. Purba Joshi, IIT Bombay, India
Akanksha Singh, IIT Bombay, India

Abstract

The study aimed to understand the role of physical mock-ups in the ideation phase while designing building components for the selected regions of extreme weather conditions in India. A thematic analysis was conducted to identify the emerging themes from a set of student projects that represented the initial ideas using sketching and physical mock-ups during ideation.
Today the use of physical mock-ups is limited to evaluating ideas that are already developed using sketching. Prior research promotes using physical mock-ups as an effective tool to generate new ideas, as it supplements the designer's incorrect mental models and enhances the creativity and functionality of the ideas. Also, focusing on physical mock-ups when used along with external representations like sketching and role-play should result in better positioning and instructions in contemporary Product Design education. The first part of the paper describes the stages involved in the design of the research study, which followed the Sketch > Mock-up > Sketch (SMS) ideation process. The second part of the paper describes the six-phase thematic analysis to examine and analyze the data to develop themes from ten student projects. The third part of the paper describes the five emerging themes and findings to highlight the importance of physical mock-ups in the ideation process, along with other forms of external representations like sketching and roleplay.

Product Design; Design Process; Physical Mock-ups; External Representations; Thematic Analysis

Designing is an intricate activity, and the outcome involves the manipulation of the designer's internal representations, which is vital to innovation (Christensen and Schunn 2009). However, the inadequate internal representations give rise to the need for external representations of the idea, such as sketching, physical mock-ups, role play, etc. The information available about physical mock-ups in the ideation phase is conflicting. No guidelines are available to address the real-life scenario of using a hybrid or flexible external representation approach. The research so far has focused more on the role of physical mock-ups quantitatively. There is a need to qualitatively evaluate the effects of using it along with other forms of external representations, especially sketching.

Literature Review

Physical Mock-ups have been instrumental over the centuries in producing innovative representations to better connect with different stakeholders' expectations (Sanders and Stappers 2014). In the initial process of design, the concepts are still fluid and can be improvised quickly. The physical mockups help the designers externalize the thought process for better visualization and reworking, forming a feedback loop that Robert McKim calls ‘etc’ (etc: express/ test/ cycle). McKim proposes constructing a three-dimensional structure as one of the ways of expressing visual ideas along with other ways, such as acting them out, talking about them, writing them down, and drawing them (McKim 1972).

Researchers and experts describe physical mock-up making as a way for designers to explore form, composition, and functionality from idea to detail design. Also, physical mock-ups are defined as a problem-solving tool, a kind of culture and language, and experts strongly recommend frequent use of physical mock-ups in the design process (Kelley 2001) (Isa, Liem, and Steinert 2015). Designers, engineers, and artisans use physical mock-ups to ideate, visualize and refine product ideas. Making a three-dimensional object by hand requires skill and knowledge of form, proportion, and construction. In this context, Marks and Kelly support the existence of physical mock-ups and reject the notion of ultimate dependency on virtual models as tools for solving all design problems (Kelley 2001) (Marks 2000). However, in recent years, Computer-Aided Design (CAD) has seen increased attention in the idea generation stage (Joshi and Chakravarthy 2021). Many researchers believe that the designer should be careful in resorting to physical mock-ups as considerable time, effort, and cost is involved, which may influence the design decision and directions over time. This limitation is known as design fixation, and to counter this view, researchers also propose that the fixation is a general phenomenon induced by many other factors present in all other representations (Christensen and Schunn 2009) (Baxter 1995). The literature so far suggests that limited qualitative studies were conducted in the context of physical mock-ups as a generative tool in the ideation phase.

Research Method

Thematic analysis is one of the most used methods in Qualitative Data Analysis (QDA). Instead of counting the frequencies of occurrence of phrases and words, it focuses on identifying and describing the patterns within the data, which can be characterized as themes (Guest, MacQueen, and Namey 2014). Themes can also be defined as ‘abstract (and often fuzzy) constructs’ that link not only expressions found in texts but also expressions found in images, sounds, and objects. The qualitative analysis of the content involves searching through the data using the inductive approach to identify the connections and patterns which can become themes (O’Leary 2017). Braun and Clarke proposed a Six phase model to conduct thematic analysis and emphasized that it is not a linear model but a recursive process (Braun, V. and Clarke 2006).

Thematic Analysis

The Design task required the students to work on the building components of a rural house as per the identified problems in the report by UNDP, India (United Nations Development Programme). From the UNDP reports and secondary research, a re-defined brief and a set of design priorities were derived for the selected region. Analogies to generate ideas (direct, symbolic, fantasy, and personal analogy) were used to explore innovative solutions (Sinha and Chakravarthy 2013).

The Design task was divided into three stages consisting of Sketch (S), Mock-up (M), and Sketch (S) (SMS ideation process). In the first stage, the students were asked to generate as many ideas as possible using analogy to ideate and sketch to represent the ideas. During the second stage, the students selected a few ideas to demonstrate the solution using physical mock-ups. In the third stage, the students documented the journey from sketches to physical mock-ups with refined sketches of the final idea. The initial ideation sketches were made in the studio environment, and the physical mock-ups were made in the workshop using various materials such as thermocol, hard boards, thick paper, wood, bamboo sticks, wire mesh, etc., and utilized cutters, scissors, and hand tools as required. The data consisted of presentations, images of the physical mock-ups, and feedback on the mock-up building activity.

Braun and Clarke's Six phase model was used to conduct the thematic analysis, which is as follows.

Phase 1: Familiarization with the data

Common to all forms of Qualitative Data Analysis, immersion and becoming intimately familiar with the data was required. It was achieved by reading and re-reading the data to note initial observations. All 10 cases were studied in detail concerning all three stages of the ideation process, and preliminary observations were made.

Sample case 1

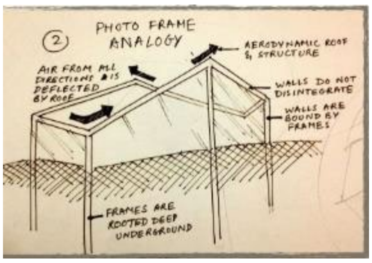
<table>
<tr><td colspan="3">Case 1 - Structures for Storm-Resistant Housing in Tripura</td></tr>
<tr><td>Stage 1- Initial Sketch (S)</td><td>Stage 2 - Physical mock-up (M)</td><td>Stage 3 - Refined Sketch (S)</td></tr>
<tr><td>
</td><td></td><td></td></tr>
<tr><td>Champion idea – Photo frame analogy</td><td>Ideation continued during the mock-up stage (tie beams)</td><td>Concept evaluated for form, function, and construction</td></tr>
</table>

Figure 1: Stages of Ideation

Initial observations

- The final idea evolved from combining the champion idea with subsidiary ideas and improvising it during the mock-up stage. During the evaluation of the idea for function using physical mock-up, tie beams were introduced, indicating continuation of ideation.
- Combining different ideas to make a unified concept happened during the mock-up making stage while the subject tried to iron out all the issues.

- Paper offered flexibility in making different parts of the mock-up, like the hollow external wall, the pile foundation, and the house.

Phase 2: Generate initial codes

A reflective thematic analysis was conducted with an open coding method to evolve codes. As per the coding strategy, all 10 cases were coded using CAQDAS (Computer-Assisted Qualitative Data Analysis Software, MaxQDA). In this phase, a set of codes, along with relevant data extracts, were generated.

Phase 3: Search for themes

This phase involved grouping the codes based on similarity to form initial code categories. The codes generated from all 10 cases were clustered based on their affinity and refined further to arrive at code categories which eventually led to themes.

Phase 4: Review and refine codes and categories

This phase involved rechecking whether the codes, categories, code extracts, and the entire data set work together as themes. Also, re-evaluate whether the themes narrate the story about the data and outline the nature of individual themes.

Phase 5: Define themes

This involves giving a meaningful and precise name to each theme and detailing the analysis of each theme based on the relevance of the data. The code categories were further grouped, and themes were defined for each category as per their common links to form a theme.

Phase 6: Writing up themes

This phase involved writing the analytic narrative with data extracts to make observations and arrive at conclusions. The baselined codes were re-applied to the data to check the applicability and arrive at data interpretation with themes.

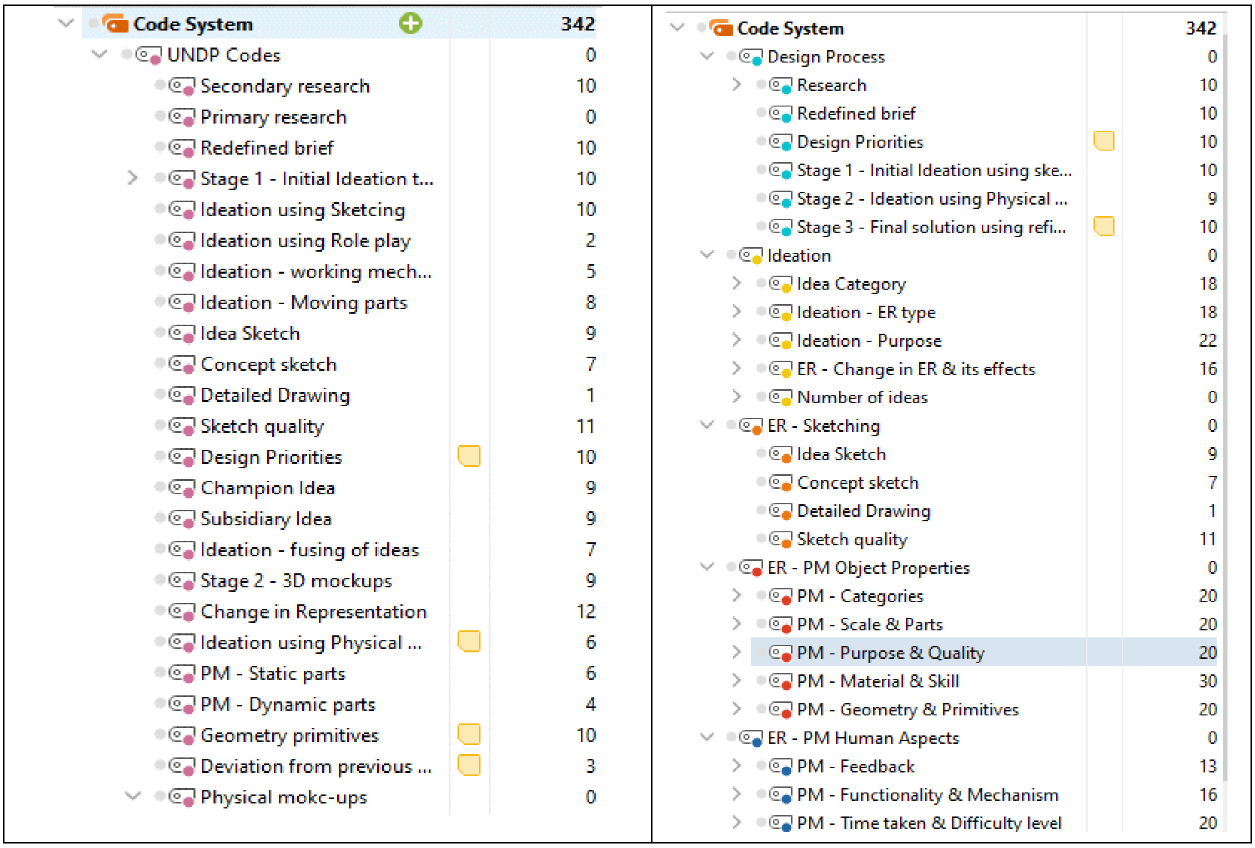


Figure 2: From initial open codes to categories using the Max QDA tool

Interpretation of data with themes

The following themes emerged from the reflective thematic analysis.

Theme 1: Design process

Initial Research, Redefined Brief and Design Priorities

Initial research leads to a redefined brief and a set of design priorities. Ideation is carried out based on the redefined brief and inputs from research. Design Priorities act as a guide for ideation, later to evaluate ideas at stages 1 and 2 and help narrow down to a champion idea and a few subsidiary ideas.

Ideation Stages

In stage 1, ideas are generated using sketches with annotations and directional arrows. The students generated as many ideas as possible using analogy to ideate, and the first level of screening of the ideas took place using the design priorities. A champion Idea and a few subsidiary ideas are selected to continue ideation in stage 2 using physical mock-ups. At stage 2, the students continued ideation using physical mock-ups made from any available low-cost material. At this stage, there was scope to incrementally improve the idea by fusing the champion and subsidiary ideas or refining the champion idea for form, function, and construction. At stage 3, the student documented the journey from initial ideation sketches and physical mock-ups to the final refined solution to showcase the creative visualization process. No improvement to significantly less improvement of the idea is noticed at this stage.

Ideation can be categorized as open ideation (no constraints) or closed ideation (based on re-defined briefs and priorities). Open ideation without considering any Design priorities gives more scope to continue ideation even at stage 2. In contrast, closed ideation, with a re-defined brief and design priority, can be more focused based on requirements and may restrict the continuation of ideation in stage 2.

Theme 2: Ideation

Ideation Purpose and External Representation

In stages 1 and 2, role play also supports ideation. Sketching as an external representation initially helps visualize form, proportions, and the working mechanism shown through directional arrows and annotations.

Overall, the purpose of the ideation using the physical mock-ups is to visualize form, function, and construction. Continuation of ideation is noticed in some cases, even during the physical mock-up making, by either refining/ detailing the idea or by trying to fuse the subsidiary ideas into the champion idea. The scaled-down physical mock-ups were made within half a day, which helped the students to visualize/ refine the forms, understand/ re-work the function, and also to fuse different ideas to make a new idea. The working mechanism usually has moving parts based on scientific principles, like a telescopic structure. A lack of building skills forces the students to make physical mock-ups with static parts instead of moving parts, and the movement is simulated internally.

Speculation is the time spent correcting the mental model while making the physical mock-ups. At this stage, along with updating the mental models, it also reveals new situations while addressing the hidden parts of the idea.

Idea Category and Fusion of Ideas

The fusion of ideas first takes place partially at stage 1. It continues in stage 2 by fusing the champion and subsidiary ideas, indicating that there is more scope for the fusion of ideas while making the physical mock-ups. The fusion of subsidiary-focused ideas into the main champion idea often produces an incremental or radical change. The fusion introduces complexities in geometry and moving parts, and physical mock-ups played a role in visualizing it to handle the increased level of complexity, which would have been difficult to represent using sketching.

Theme 3: Sketching

In stage 1, most of the sketches fall under the category of Idea sketches (Pei 2009), and the quality of the sketches ranges from very basic to moderate. It improves from idea sketches in the ideation to concept sketches in the refined final solution. However, the Doodles are absent in ideation, which could have retained the essence of the idea at a high level so that the scope of developing a new set of ideas in the next stage could have been more. In some cases, a lack of skill in the drawing may have led to low-quality sketches, which increased the scope of using physical mock-ups to ideate in stage 2.

In some cases, although the quality of sketches is basic, the ideas that are generated with more details give less scope to continue ideation using physical mock-ups. The quality of sketches and level of completion of the idea influences the scope for the continuation of the ideation at the next stage. The Sketching skill does not affect the idea-generation process, and physical mock-ups can compensate for the lack of quality in sketching. In most cases, a good skill in sketching may have prevented effective ideation using physical mock-ups, except in one case, a good skill in sketching did not hinder physical mock-up-making in any way. The orthogonal sketches indicate low skill level, but ideation still generated good quality ideas.

Theme 4: Physical Mock-ups – Object Properties

Physical Mock-ups as External Representation

All the physical mock-ups fall under the category of Explorative form and/or function mock-ups (Subramanya and Chakravarthy 2019). Focussed function mock-ups are made when the working mechanism is explored, and comprehensive mock-ups are made in both cases. A comprehensive physical mock-up can also be a collection of many focused ideas. The focused physical mock-ups that explore a working mechanism with moving parts, have 3 to 5 parts. The comprehensive physical mock-ups have three or less than three parts that mainly explore the form.

The scale of the physical mock-ups in all the projects is scaled down, and all the mock-ups are of basic quality except one, which is of moderate quality. Different scales are used to make Physical mock-ups, but the overall size remains from (10x10x10) cm to (25x25x25) cms. The tendency is to have a size that is handheld and manageable.

Material, Cost, and Building Process

Any available low-cost and flexible material in and around the workshop was used. Thermocol and thick paper are the most preferred materials, in addition to plastic pipes, metal wires, wire mesh, corrugated sheets, sliding plastic bars, and bamboo strips. Usually, one or two primary materials are used to build the mock-ups, along with accessory materials like plastic pipes, metal wires, etc. In all cases, the cost of the material is low except when thick boards and wood are used. Building skills are basic in nature, and the skill required to build the mock-ups is mainly to cut, bend and stick using glue and pins.

Physical Mock-ups – Geometry and Primitives

Although many types of geometry are used, planar and rectilinear geometry is the most preferred (Hannah 2002). If there is a lack of skill in making curvilinear forms, it is replaced by rectilinear forms at the physical mock-up stage, and in functional mock-ups, it may not affect the idea much. A geometry primitive is an existing object like a plastic pipe that can be directly used to build mock-ups, and the most preferred geometry primitive is plastic pipes of various diameters, which can fit into one another. Available Geometry primitives help build mock-ups quickly, as demonstrated in many cases, to visualize the telescopic working mechanism.

Theme 5: Physical Mock-ups – Human Aspects

Feedback and Functionality

In most cases, the finalized idea from stage 1 is visualized for form, function, and construction to get evaluative feedback rather than generating new ideas. In some cases, although the mock-up-making activity started for evaluative feedback, it gradually shifted to reflective feedback. As in the case of storm-resistant housing, tie beams are introduced during the mock-up-making stage, indicating reflective practice and speculation. Similarly, in the case of affordable rural housing, the positioning of the scales is refined based on the airflow simulated by a hair dryer. The feedback can start from either a reflective or evaluative perspective; it goes into a loop when one speculates on an idea, and ideation continues with incremental changes introduced to improvise the idea.

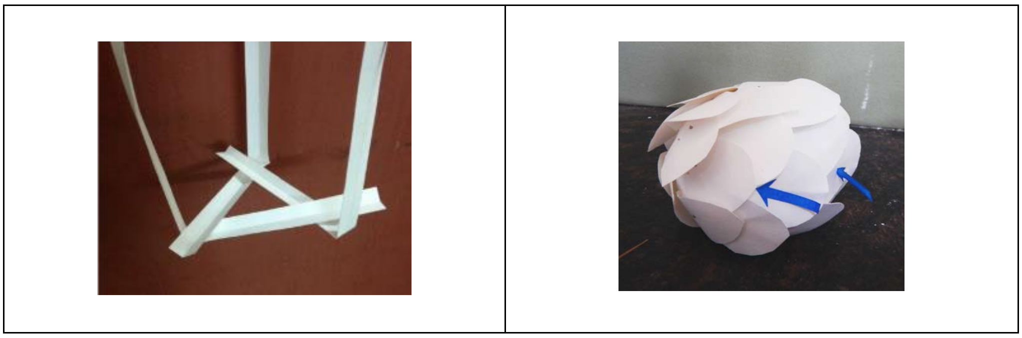


Figure 3: Continuation of ideation (Left: tie beams introduced in the Physical mock-ups, Right: Simulation of the environment to re-position the scales)

Time taken and Difficulty Level

The overall time given to complete the mock-up-making activity was half a day; in most cases, the time taken to build the mock-ups ranges from less to moderate time with a basic level of difficulty. In two cases, the time taken was moderate, either due to the material (wood and hardboard) or due to many moving parts with complex assembly (Bow and arrow), which introduces a moderate level of difficulty in building the mock-ups.

Figure 4: Material and Difficulty level (Left: hardboard with static parts, Right: Wood with moving parts)

Fixation and Skill Proficiency

Most of the students are advanced beginners (Dreyfus 2004) (Honken 2013), as they can decide on the materials and build the physical mock-ups with minimum supervision. An advanced beginner can handle physical mock-ups with dynamic parts and moderate difficulty levels in less time if the basic quality is maintained.

No fixation was observed as the materials were low cost, flexible and the time spent on building it was less except in the case of the cost-efficient roof (Fig 4, Right); the fixation ranges between basic to moderate because of the material (wood) and precision required (bow and arrow movement). Building material, cost, and skills contribute to the time taken to build the mock-up and directly affect the fixation.

Findings and Discussions

From the themes generated, the following findings emerged.

• The Sketch > Mock-up > Sketch (SMS) ideation process gives enough scope to the subjects to use the physical mock-ups in the ideation phase more as an evaluative tool than the generative tool. Improvising the existing idea has more scope than creating an entirely new idea while making physical mock-ups (themes 1 and 2). The physical mock-ups allow the designer to simulate the context to evaluate the idea and play with it to expand the possibilities early. The findings show that the exploration of the idea continued while making the mock-ups, suggesting that mock-ups were not used merely to convert the 2D sketch into a 3D physical mock-up which is in line with the previous research studies (Isa, Liem, and Steinert 2015) (V. K. Viswanathan and Linsey 2010).

• An increase in the number of parts, complex assembly, moving parts, and the rigidity of the material like wood increases the difficulty level of building the mock-ups leading to an increase in time taken that can act as factors contributing to fixation (themes 4 and 5). The findings support the earlier research on fixation (Baxter 1995) (V. Viswanathan and Linsey 2011).

• The possibility of fixation exists at all design process steps, and appropriate measures should be taken to avoid it. Early fixation has a cascading effect on the rest of the Design process and should be avoided (theme 5). The skill proficiency level of advanced beginners, as per the Five-Stage Model of Adult Skills Acquisition by Dreyfus, was able to handle a moderate level of difficulty in less time leading to no fixation (themes 4 and 5) (Dreyfus 2004) (Honken 2013).

• The purpose and type of the physical mock-ups are interlinked. Large-sized products are divided into many parts to make focused mock-ups. The tendency is to make the physical mock-ups only until the mental model is corrected or confirmed (all themes). This further confirms the findings from earlier research that the uncertainty is reduced by making mental operations aided by physical mock-ups in this study (Christensen and Schunn 2009).

`• Reflective and Evaluative feedback goes in a loop when both are present in the exploration (theme 5), which is in accordance with Robert McKim's 'etc' (etc: express/ test/ cycle) (McKim 1972).

At stage 1, instead of Idea/ concept sketches, Doodles would have given more opportunity to continue ideation while making the physical mock-ups. If the sketches are focused or comprehensive, the tendency is to make the same type of physical mock-up (themes 2 and 3). The subjects could have innovated more if they had more time and options for making mock-ups for different ideas with iterations. Being aware of the contributions of the physical mock-ups could have led to the continuation of ideation at stage 2. Ideation methods using physical mock-ups are an opportunity to explore. Different strategies can be developed to make radical changes to the existing ideas. The ideas interacting to improve the existing idea or generate a new one need to be studied in detail (themes 1 and 2).

While starting with evaluative feedback, a switch happens in thinking from evaluative to reflective. Speculation is a way of switching mechanisms to shift from evaluative to reflective feedback, which needs further study. The absence of speculation also indicates no reflective feedback (themes 2 and 5). Evaluating the working mechanism with moving parts using a physical mock-up needs better visualization and building skills (themes 4 and5). An in-depth study is required to build the students' skills while making the physical mock-ups with moving parts.

Future studies should consider actual materials' influence and properties compared to mock-up materials. Also, the role played by the existing geometry primitives, like cylindrical pipes, etc., should be explored to specifically provide primitives for making the physical mock-ups quickly. There is scope to change the order of sketching and physical mock-up-making activities based on the student's skill level. The faculty should be aware of the skill levels of the student to suggest the order of the stages. Collective learning while making physical mock-ups could be explored by adopting community-based approach which can involve student communities.

Design education traditionally has emphasized sketching and its use in creative explorations and now is supporting the use of CAD as an alternative representational tool. The education needs to pay more attention to the development of 3D visualization using physical mock-ups and their uses in correcting mental models. The use of physical mock-ups, along with other external representations like sketching and role play, should be explored further.

References

Baxter, Mike R. 1995. Product Design: Practical Methods for the Systematic Development of New Products. Chapman and Hall.

Braun, V. and Clarke, V. 2006. "Using Thematic Analysis in Psychology." Qualitative Research in Psychology, 77–101.

Christensen, Bo T., and Christian D. Schunn. 2009. "The Role and Impact of Mental Simulation in Design." Applied Cognitive Psychology Appl. Cogn: 327–344.

Dreyfus, Stuart E. 2004. "The Five-Stage Model of Adult Skill Acquisition." Bulletin of Science, Technology and Society 24 (3): 177–81. https://doi.org/10.1177/0270467604264992.

Guest, Greg, Kathleen MacQueen, and Emily Namey. 2014. "Introduction to Applied Thematic Analysis." Applied Thematic Analysis, 3–20. https://doi.org/10.4135/9781483384436.n1.

Hannah, Gail Greet. 2002. Elements of Design: Rowena Reed Kostellow and the Structure of Visual Relationships. Princeton Architectural Press.

Honken, Nora. 2013. "Dreyfus Five-Stage Model of Adult Skills Acquisition Applied to Engineering Lifelong Learning Tools for Assessing Level of Expertise and Determining Appropriate Instruction , Assignments and Feedback to Enhance an Employee ' s Human Capital."

Isa, Siti Salwa, Andre Liem, and Martin Steinert. 2015. "The Value of Prototypes in the Early Design and Development Process." In DS 80-5 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 5: Design Methods and Tools-Part 1, Milan, Italy, 27-30.07. 15, 235–42.

Joshi, Purba, and Battula K Chakravarthy. 2021. "Investigating the Use of 3D Solid-Modeling Tools in the Early Idea Generation Stage of Product Design: An Exploratory Study." In Design for Tomorrow---Volume 3, edited by Amaresh Chakrabarti, Ravi Poovaiah, Prasad Bokil, and Vivek Kant, 107–16. Singapore: Springer Singapore.

Kelley, Tom. 2001. "Prototyping Is the Shorthand of Innovation." Design Management Journal (Former Series) 12 (3): 35–42.

Marks, P. 2000. "Faster Times for Rapid Prototyping." Computer Aided Engineering 2.

McKim, Robert H. 1972. "Experiences in Visual Thinking."

O'Leary, Zina. 2017. The Essential Guide to Doing Your Research Project. SAGE Publications India Pvt Ltd, New Delhi.

Pei, Eujin. 2009. "Building a Common Language of Design Representations for Industrial Designers and Engineering Designers." Loughborough University.

Sanders, Elizabeth B.-N., and Pieter Jan Stappers. 2014. "Probes, Toolkits and Prototypes: Three Approaches to Making in Codesigning." CoDesign 10 (1): 5–14. https://doi.org/10.1080/15710882.2014.888183.

Sinha, Sharmila, and B K Chakravarthy. 2013. "A Design Inquiry into the Role of Analogy in Form Exploration: An Exploratory Study." In ICoRD'13, edited by Amaresh Chakrabarti and Raghu V Prakash, 175–86. India: Springer India.

Subramanya, T N, and B K Chakravarthy. 2019. “Standardization of Terminologies for Physical Models in Design Process.” In Research into Design for a Connected World: Proceedings of ICoRD 2019 Volume 2, 3–20. Springer.

Viswanathan, Vimal K, and Julie S Linsey. 2010. “Physical Models in Idea Generation: Hindrance or Help?” https://doi.org/10.1115/DETC2010-28327.

Viswanathan, Vimal, and Julie Linsey. 2011. “Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost.” In International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 54860:119–30.

Subramanya T N

Subramanya is a Research Scholar at IDC School of Design, IIT Bombay, and a faculty at Srishti Manipal Institute of Art Design and Technology.

He has a Bachelor’s degree in Architecture and has done post-graduation (M. Des) from IIT Kanpur. His Ph.D. at IIT Bombay is in the ‘Role of physical Mock-ups in the idea generation phase of new product development’.

His areas of interest are Human-Centered Design, Thinking by making, and creativity.

Dr. Chakravarthy B K

Prof. B. K. Chakravarthy teaches Innovation by Design at the IDC School of Design, IIT Bombay. After his Post Graduate Degree in Design from IIT Bombay, he undertook active research in the area of new product innovation and obtained a Ph.D. at IIT Delhi.

Dr. Chakravarthy specializes in the area of innovation by design which encompasses new product innovation processes and methodology. He has been instrumental in bringing Industry projects to the classroom. Some of his most notable products are the Z-Line gasoline dispenser and the maintenance-free Letterbox for India Post, which has been design success stories in India for which he has been awarded the Faculty Research Fellowship for India Post.

His research and consulting spans across Design Strategy, Humanizing Technology, Disruptive New Product Innovation, and Collaborative Innovation Methodologies. He has set up the Shenoy Innovation Studio at IDC, IIT Bombay. Using live projects, the studio works with the aim to Humanizing Technology to solve problems under his leadership as Director.

Dr. Purba Joshi

Purba Joshi is an Associate Professor of Industrial Design at IDC School of Design, IIT Bombay.

She has done her Bachelor’s degree in Electronics and Telecommunication Engineering and her post-graduation (M. Des.) in Industrial Design. Her Ph.D. in the area of CAD and creativity from IDC School of Design, IIT Bombay.

She works extensively in the area of product design for healthcare. Other research and consultancy work areas include packaging design and designing for special needs.

Akanksha Singh

Akanksha Singh is a Design Innovation and Research fellow at the Shenoy Innovation Studio, IDC School of Design, IIT Bombay. She holds a bachelor's degree in design from NIFT Raebareli and a Master's Degree in design from IIT Hyderabad. With a focus on public spaces, she has undertaken various projects and curated experiential initiatives that cater to the interactions and affordance of those spaces.

Her areas of interest are Sensory design and storytelling, Design thinking and innovation, Human Centered Design.

From Prototype1.0 to Prototype3.0: Situated learning in Prototype design for Chinese labour education

Linlin Yang, College of Design and Innovation, Tongji University
Shangjie Zhang, College of Design and Innovation, Tongji University
Danqing Meng, Institute of Higher Education, Tongji University
Ziwen Lu, College of Design and Innovation, Tongji University
Fei Fan*[1], College of Design and Innovation, Tongji University

Abstract

China has promoted labor education to an important position in the education. Based on the background of middle school labour education reform. In order to explore the product prototype in labor education, this paper applies Situated learning theory to analyze the factors in labour education to support whole process of product prototype design. By combining the basic characteristics of Situated learning theory with the Define, Ideate, and Prototype stage of design thinking, we developed Prototyope1.0 for one school. Further, we apply the teaching mode of Situated learning theory to test the prototype and guide the upgrading of prototype products. By summarizing the experiential knowledge of the prototype after every iteration, the practice field of labour education has evolved into a community of practice from prototype1.0 to prototype3.0.

Prototype design; Experiential knowledge; Chinese labour education; Situated learning theory;

Introduction

Since 2018, China has begun to attach importance to implementing labor courses in schools. In 2020, the "Opinions on Comprehensively Strengthening Labour Education in Colleges, Middle Schools and Primary Schools in the New Era" emphasized that labour education has the comprehensive educational value of cultivating morality, increasing intelligence, strengthening physical fitness, and improving aesthetics. This policy has promoted labour education to an essential position in the education system and provided fundamental guidance. However, how to organize and implement Chinese labour education in daily teaching practice still needs to be further explored. (Li Qun & Zhang Pingping; 2021).
The primary feature of labour education is to enable students to master both knowledge and skills in labour practice. And the labour education in schools can not be isolated from the systematic curriculum content. We bring the design perspective into educational field and found that prototypes stimulate reflections which are used by designers to frame, refine, and discover possibilities in design space (YK Lim & E Stolterman & JD Tenenberg; 2008). In the field of school

[1] *Corresponding author. E-mail address: 04050@tongji.edu.cn

labor education, we use the prototype to reflective practice, optimize the product design of labor education, and provide teaching aids for labor education courses. Under the background, this study follows the design prototype project of labour teaching product in two middle schools in Shanghai.

With interdisciplinary research methods, design thinking is applied to the course conception and design, combined with education theories to explore the function and effectiveness of its prototype products. Experiential knowledge can then be generalized based on prototype research feedback. The continuous improvement of prototype 1.0 to prototype 3.0 was achieved through the practical feedback and collaborative process of the prototype in design research among practitioners, R&D, and academia.

Theoretical Background

Situated learning theory or situated cognition theory has been a popular topic in western learning theory since the 1990s. This theory is founded on the reflection of learning theory and addresses the needs of school practice.

Situated learning theory is based on situated cognition. Representations have been viewed as the essential concern of cognitive science, yet few studies have examined how people create, perceive, and attribute meaning to new representational forms.(William J, 1993) Vidulich M.(1994) synthesized research on the situated theory and believed that situated cognition is the integration of information obtained through the environment and one's own knowledge to form an integrated understanding of mental perception, the meaning of events, and the ability to anticipate the consequences of taking or failing to take particular actions. David H.(2000) and Thomas M. Duffy(2003) extended this theoretical research from the "practice field" to the "communities of practice". The social relations of apprentices within a community change through their direct involvement in activities, and, in the process, the apprentices' understanding and knowledge skills develop. More importantly, the identity of the "learner" no longer belongs to a fixed category but a dynamic and generative concept. Members of communities become genuine practitioners.

Situated learning theory believes that the essence of learning is the process of individual participation in practice, the interaction with others and the environment. (Liu&Gao, 2010), According to two articles named *Analysis of Situated Cognitive Learning Theory and Situated Cognitive Teaching Model* (Liu&Gao, 2010) ,and *Situated learning: Multiple perspectives* (McLellan H, 1996), the theory holds that learning has the following characteristics and the following teaching models.

Situationality

Learning and acting are indistinct, learning being a continuous, life-long process resulting from acting in situations.(Brown et al.,1989) It emphasizes that the situation is a necessary condition for learning to occur and proceed, and the situation also has the function of clue guidance, helping to retain learning knowledge.

Authenticity

Brown et al.(1989) referrd that students may pass exams (a distinctive part of school cultures) but still not be able to use a domain's conceptual tools in authentic practice. It emphasizes that learning occurs in real-world situations, including both physical and cognitive authenticity. Physical authenticity including practicing in real-space scenarios such as companies. Cognitive authenticity refers to professionals engaging in professional activities.

Practicalness

It emphasizes that learners must actively engage in practice related to the professional field rather than relying on textbooks or teachers' experience summaries. Learners should pay attention to the methods of discovering, analyzing, and solving problems related to the professional field and truly understand the knowledge content.

Inquiry

Give learners the right to inquire, that is, to be exposed to real dilemmas and find solutions. Learners need to feel responsible for the solutions, not just rely on what teachers can offer, but to develop their professional thinking.

Proactivity

Inspire learners' motivation for active learning and provide diverse learning resources. For example, design real problem situations, provide appropriate demonstration and guidance, give students a sense of meaning and achievement in the learning process, and stimulate students' learning motivation.

Under the support of the Situated learning theory, teaching modes have also emerged in teaching practice, mainly including the following three types: anchor-casting teaching mode, cognitive apprenticeship teaching mode and interactive teaching mode.

Anchor-casting Teaching Mode

This mode uses multimedia technology to present an accurate and interesting story to attract learners and bring them into complex situations. Determining a problem in a situation is compared to "casting an anchor". The teaching content and process are based on the problems that have been determined. The anchor-casting teaching mode enables students to generate learning needs in a complete and actual situation and, through the interaction among members of the learning community, complete the whole process of identifying, proposing, and achieving goals with their activities as well as generative learning. The main objective of this teaching mode is to create a situation that enables students and teachers to continue to explore meaningful problems, and help learners understand the types of problems. And then observe how experts or teachers use knowledge to clarify, represent and discover problems, and make learners identify, discover, and solve problems in the same situation from multiple perspectives to integrate their learning.

Cognitive Apprenticeship Teaching Mode

Brown and Collins proposed the basic framework and elements of the cognitive apprenticeship mode. This model includes four components: content, method, sequence, and sociality. (Gao, 2001) The range includes disciplines knowledge, problem-solving strategies, management strategies, and learning strategies. The teaching method creates opportunities for students to observe, participate and discover. Sequence refers to the construction in stages, from simple to complex, from parts to a whole, to build the skills which experts need in practical operations. Sociality requires the representation of the learning environment, the real-world features in which the learned knowledge is applied.

Interactive Teaching Mode

Interactive teaching is a learning mode in which teachers and learners cooperate. It is a constructive and open teaching method that emphasizes multi-directional interaction and cooperation between teachers and students, between students, between students and textbooks, and that completes a specific learning task while communicating and collaborating. Interactive teaching emphasizes the interaction between the learner and the environment.

According to the view of Brown et al, activity in school should be authentic, which implies that school activities should include the ordinary practice of different science cultures. The teacher's task, is to confront the apprentices with effective strategies that can be used to solve everyday problems.The goal of teaching in school is the student's acquisition of skills practiced within science communities. To accomplish this goal, different teaching techniques are used, such as modeling, coaching, scaffolding.(Vanessa P, 2013) Therefore, Situated learning theory's model is currently mainly used to guide teaching practice. However, few studies have applied this theory to the design of teaching environments, teaching products, and teaching scenarios that assist teaching practice. We explore how Situated learning theory can be effectively applied to learning designs and the situational interests of learners. Prototypes have an effect on our thinking because they are considered best examples of a conceptual category.(Nieveen N, 2013) Taking the learning concept of situated cognition theory as the theoretical guidance of the designing process in the concept stage and implementing situated cognition teaching mode as the standard to test the prototype are essential innovations in applying the theory to the design project.

Research design and methods

From prototype 1.0 to prototype 3.0, there are two processes in prototype iteration. By applying Situated learning theory, design thinking process, participatory research, user interviews, literature research, and other methods, the prototype product design is upgraded to the prototype product service system design.

Prototype 1.0

Prototype 1.0 followed the typical design thinking process's Empathise, Define, Ideate, Prototype stage. Empathise stage: using desk research, participatory research, and user interviews to collect the school's goals of labour education, school characteristics, objective conditions, the teaching process, etc., to determine the basic needs of target users. Define & Ideate stage: The basic features of Situated learning theory were summarized through a literature review and used to guide the early stage of the design thinking process. The Define stage of design thinking was introduced to deeply explore the needs of target users and then define the functional elements that the labour education product prototype should have in the Ideate stage. Prototype stage: We designed the "Fish and Vegetable Symbiosis" prototype product.

Prototype 2.0

Prototype 2.0 followed the Test, Ideate, Prototype stage of the typical design thinking process to realize the reframing of the prototype concept. Test stage: The teaching mode of Situated learning theory was summarized to test Prototype 1.0's application effect. To collect as much data as possible and get feedback from different users, semi-structured interviews were conducted with teachers and students. Implementing the situated learning teaching mode was used as the specific evaluation rules in the target users' interviews. Ideate stage: The interview content was organized and summarized to find how much the existing Prototype 1.0 has achieved and its advantages and disadvantages. The disadvantages of Prototype 1.0 are avoided and develop further functional ideas for the unmet needs of teachers and students to upgrade the Prototype. Prototype stage: We designed the Roof Garden Planting Box prototype product system.

Prototype 3.0

Prototype 3.0 followed similar stage of Prototype 2.0. The second test was conducted by the practice of teaching mode of Situated learning theory and semi-structured interview. We increased the consideration of sociality, further optimized Prototype 2.0 to establish the teaching system, and ensured the teaching effect to be better realized. We designed the Planting Box equipped with Labour Education Web version and Applet version prototype product service system.

The process of designing, testing and redesigning the Prototype of Chinese labor education is through the collaborative participation of research and practice. This study uses interdisciplinary research methods and takes the needs of teachers and students as the core. Moreover, The development of Prototype realizes the transformation from the "practice field" of teaching products and environment to the "practice community" of a teaching system with social attributes.

Prototype Design Practice and Analysis

Design thinking is a problem-solving process that focuses on the end-user's needs and their experience to generate better product solutions.(Crandall,2019) The design process of Prototype 1.0 follows the typical design thinking process, and the Define and Ideate stages of design are integrated into the characteristics proposed by the Situated learning theory to clarify the functional elements and design the product prototype, as shown in figure 1. In the Prototype stage and Test stage of the design process, the application of the teaching mode of the situated theory is used as the evaluation standard to test the application of the prototype as shown in figure 2. According to the evaluation, the part that needs improvement was brought into the redesign of the prototype. The following will introduce Prototype 1.0 to the Prototype 3.0 design practice.

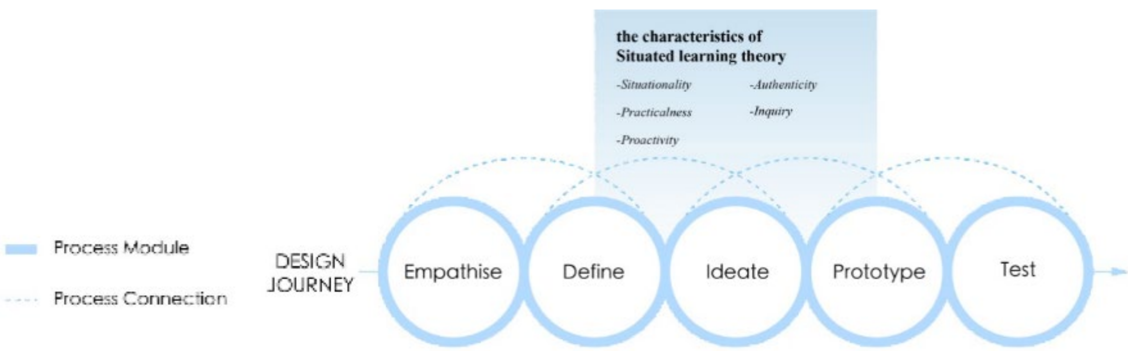


Figure 1 the Situated learning theory’s characteristics in typical design thinking process

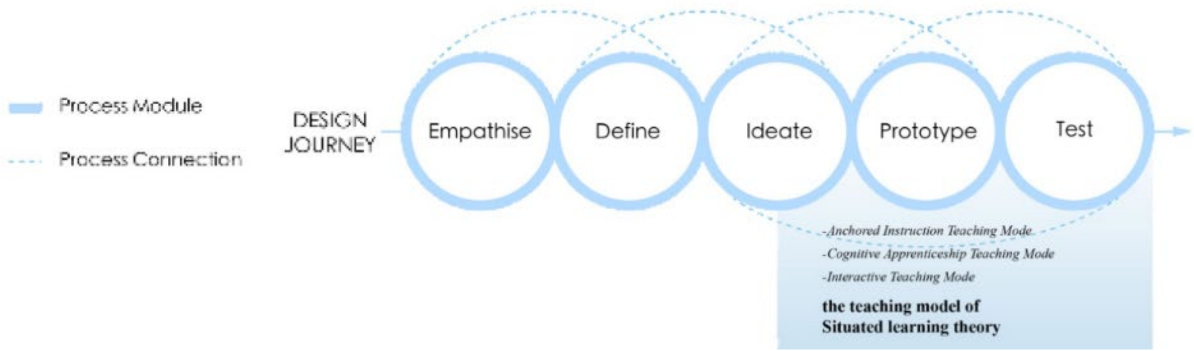


Figure 2 the Situated learning theory’s teaching model in typical design thinking process

1) Prototype 1.0: Shanghai X Middle School of Design and Innovation-"Fish and Vegetable Symbiosis" Product Prototype

The design practice of Prototype 1.0 was carried out at the Shanghai X Middle School of Design and Innovation. With the goal of "ecological education", the school plans to adopt the PBL teaching method to carry out labour education. Based on this, a combination of teaching, practice and creation was designed for it. The "Fish and Vegetable Symbiosis" product prototype, in the limited teaching space inside the school building, combines aquaculture and hydroponics and applies to an integrated product system. By simulating the natural environment where animals and plants grow, fish and vegetables provide the nutrients they need for each other and are self-sufficient. Fish farming does not need to change the water, there is no water quality concern, and vegetables can grow generally without fertilization. labour education is carried out in this ecological symbiosis system, which realizes the teaching of the combination of multidisciplinary knowledge and labour practice.

Empathise stage

The Middle School is located near the Bund in Shanghai, with a superior geographical location. It is an open innovation platform for high school students in Huangpu District. It provides services such as innovative social practice, innovation achievement display, entrepreneurial cooperation, school-enterprise exchanges, and international exchanges for high school students in Huangpu District. The existing curriculum system at the school includes 40% of innovative courses based on real-life scenarios. The school's labour education needs innovative, urban, and technological attributes to better integrate with the school's existing situation.

In addition to researching the teaching needs of the middle schools, we also analyzed the demands of the users of labour education product prototypes: teachers and students. For teachers they hope to meet their own interdisciplinary knowledge teaching needs and provide real teaching venues, etc. Students need rich learning forms and can get feedback and motivation for learning, etc. The Affinity Diagram research method is used to identify target users, which summarized the requirements, as shown in figure 3 below.

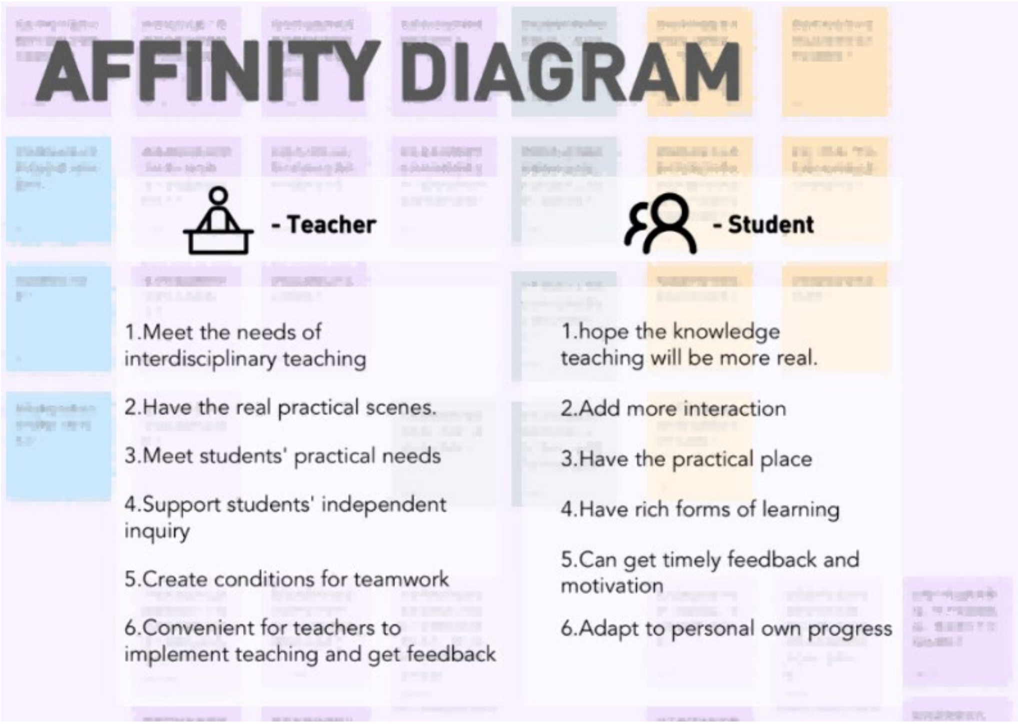


Figure 3 Affinity Diagram research of teacher and student

Define stage

In order to define labour education, it was analyzed with the help of Situated learning theory. Corresponding to the five learning characteristics proposed by it for labour education, the characteristics that the prototype of the labour education product should be defined as figure 4 follows:

Situationality	farming situations, urban agriculture, working situations, teaching context
Authenticity	cultivation, existing products, relevance to existing curriculum
Practicalness	hands-on work, actively engage
Inquiry	multidisciplinary knowledge, independent exploration in-depth professional thinking
Proactivity	multiple teaching methods & resources, non-traditional classroom

Figure 4 the ideas of the labour education product's prototype characteristics

a) Situationality.

The labour situation is a necessary condition for the occurrence and progress of labour education. It has the function of clue guidance and is helpful for the retention of labour knowledge.

b) Authenticity.

Labour education occurs in real events, and the prototype of labour education products must contain real working situations or the actual process of professionals engaging in professional activities. This is also the core of PBL teaching, that is, learning from real-world problems.

c) Practicalness.

Students should actively engage in labour practice and hands-on operations, not just read textbooks and listen to teachers' teachings. The prototype of labour education products needs to enable students to discover, analyze and solve labor practice problems to understand the detailed content truly.

d) Inquiry.

Students must have the ability and space to conduct an independent inquiry, which requires necessitates the use of labour education product prototypes to provide in-depth exploration space, integrate multidisciplinary knowledge, and assist students in developing in-depth professional thinking.

e) Proactivity.

The prototype of labour education products should arouse students' motivation for active learning and provide learners with diverse labour learning resources. Design interesting and real-world problem situations, for example, and provide appropriate demonstration and guidance so students can have a sense of meaning and achievement in the learning process, stimulating their learning motivation.

Compared with traditional labour, positioning the scenario in urban agriculture includes basic labour processes such as planting and cultivation and extended content such as system design thinking, technology popularization, and green environmental education involving biology, chemistry, and physics. Finally, a typical case of circular farming-the "Fish and Vegetable Symbiosis" product was selected as the theme of the labour education, guiding the development of labour education courses and practices.

In addition to researching the teaching needs of the middle school, we also explored the needs of the users of labour education product prototypes, that is, teachers and students. Based on the characteristics of the Situated learning theory: situationality, authenticity, practicality, inquiry, and proactivity, the users' research results are summarized.

Ideate stage

Based on the "Fish and Vegetable Symbiosis" product, the corresponding course development is carried out, and the function of the labour education product prototype is gradually formed from the content. In this courses, Students must first learn how to apply the two technologies of aquaculture and hydroponics into one system through ecological design so that animals, plants, and microorganisms can achieve a harmonious ecological balance relationship and understand the sustainable cycle in a low-carbon production model. In this course, students have the opportunity to try different media for plant cultivation, such as substrate cultivation based on gravel or ceramsite, deep-water floating raft cultivation using floating materials such as foam to build floating platforms, and pipe cultivation using PVC pipes as planting carriers. Cultivation, in which the water for fish farming is directly atomized and sprayed onto the roots of plants. In the end, students will also observe and record the various processes of aquaponics.

From the content of the course, the product prototype must contain the following features:

a) Fish pond

b) Cultivation area

c) Filter pool

d) Water pump system

e) Observation records

Prototype stage

According to the labour education course content and corresponding product functions produced in the ideate stage, the aquaponics system product prototype design is carried out as shown in figure 5. According to the existing teaching space, relatively bright and lively product prototype colours are selected, and in order to ensure the operability and safety of students, the product specifications and shapes are designed accordingly. At the same time, animals and plants that are suitable for teaching and easy to raise and plant are selected to ensure smooth teaching progress on a fundamental basis.

Figure 5 "Fish and Vegetable Symbiosis" Product Prototype

Test stage

After the prototype is designed, it is applied to the teaching practice of the X Middle School, and the feedback from students and teachers is investigated according to the application degree of the teaching mode of Situated learning theory. Based on this, the prototype test is carried out to find the opportunity point for prototype updating. The following table 1 summarizes the interviews' keywords with target users.

Three Teaching Model	Target users	Key words
Anchored Instruction Teaching Mode	teachers	"It creates a planting and observation situation for students, in which they can observe and learn independently according to the problems." "Limited by the product form, it is impossible to divide into multiple groups to cooperate at the same time." "Lack more forms of multimedia equipment to support classroom teaching and interpretation." ……
	students	"We simulated some natural temperature and moisture conditions in indoor space, and our practical knowledge could not be tested under real outdoor conditions." "It would be nice if the supporting equipment supported us to discuss and record the problems at a certain moment." ……
Cognitive Apprenticeship Teaching Mode	teachers	"Students can directly observe the process of the teacher's operation of the equipment, and practice after learning by themselves"; "With the help of the teacher, students make sure the research problems for observation, operate the equipment and record the environmental data of plant growth." "According to the disciplinary knowledge taught by teachers, students can utilize the knowledge to evaluate the operation of ecosystems." ……
	students	"We observe and record the circulation between animals, plants and microorganisms by applying the knowledge taught by our teachers. Real scenes make it easier for us

		to understand this knowledge." "Although the situation of water cycle is true, the parameters are set by the teacher, and we lack many opportunities to set up and experiment by ourselves." ……
Interactive Teaching Mode	teachers	"There is more interaction between students and teachers, and less cooperation and interaction between students." "Students can record data by the touch screen on the product, but they lack diverse interactive ways." ……
	students	"The space of each cell in the product is very limited, so it is difficult to ensure that each of us can practice in it." ……

Table 1 the interviews' keywords with target users

According to the interview summary, although we have provided a prototype of the "Fish and Vegetable Symbiosis" product prototype, an integrated product that can be taught, practiced, and created, there are some problems in prototype 1.0. In Anchored Instruction Teaching Mode, its product form cannot support multiple teams cooperating simultaneously and lacks more multimedia equipment to support classroom teaching and interpretation. The students hope to have natural outdoor conditions to practice more and need more intelligent supporting equipment. In Cognitive Apprenticeship Teaching Mode, the product prototype provides a good implementation condition for cognitive apportioning ship teaching mode. At the same time, the students need more opportunities to set up and experiment by themselves. In Interactive Teaching Mode, there is less cooperation and interaction between students and a lack of diverse interactive ways.

Prototype 1.0 provides improvement direction in teamwork, interactive content, equipment interaction, setting up natural outdoor conditions, and other aspects for Prototype 2.0.

2）Prototype 2.0：Shanghai-Y Middle School- Roof Garden Planting Box Product Prototype

According to the test feedback and experiential knowledge summary for Prototype 1.0, with the help of the project opportunity provided by Shanghai Y Middle School, Prototype 1.0 was iteratively upgraded. Aiming at the problem that middle school students in Cognitive Apprenticeship Teaching Mode have fewer opportunities for teamwork, the structure of integrated products was reconceived in Prototype 2.0's Flexibility. The product will eventually become a modular structure that can be disassembled into 24 planting boxes. The planting boxes can be used in combination or individually. It is designed to meet the need for multimedia equipment to support classroom teaching and interpretation in Anchored Instruction Teaching Mode. Students can use large-screen devices to collect data and touch controls with the intelligent central control platform. For the Interactive Teaching Mode, provide more gamified knowledge interaction methods to promote learning among students, continue and innovate Prototype 1.0, and design Prototype 2.0: Roof Garden with 24 planting boxes, as shown in figure 6.

The labour education classroom is mainly composed of group cooperation and independent learning. The planting box is placed on the roof space of the campus, and the labour education environment is changed from indoor to outdoor, completely following the real natural environment. Each planting box can carry out independent group practice by using a modular design. Students can plant in the planting box area and use the intelligent drip irrigation of supporting equipment to optimize the treatment. The module observes data and irrigates plants. The main technical components include environmental detection system, a soil detection system, a rainwater recovery system, a solar power generation system, an automatic irrigation system, a nutrient solution supplement system, a plant growth recording system, etc., to create more experimental possibilities for students.

Figure 6 Roof Garden Planting Box Product Prototype

The prototype planting box is also matched with multimedia equipment and science popularization content design, as shown in figure 7. The terminal control system of the planting box is placed in an independent area, which can also be used as a brainstorming area for students. The intelligent screen provides various interactive forms that help students observe data, draw sketches, and search for information. At the same time, implement the anchored teaching mode. In the design of popular science content, the anchor of the question is designed in the glass door in a guided manner through graphic design, and the corresponding subject knowledge is visualized in the form of knowledge graphs and cards. The study of theoretical knowledge provides more ways for independent learning and exploration.

Figure 7 multimedia equipment and science popularization content design

From Prototype 1.0 to Prototype 2.0, the prototype product design was upgraded to the prototype product system design, which was applied in the labour education practice of Y Middle School. After some time passed, the feedback from students and teachers was investigated again with the application degree of the teaching mode of Situated learning theory to retest the prototype. Similarly, the following table 2 summarizes the interviews' keywords with target users.

Three Teaching Model	Target users	Key words
Anchored Instruction Teaching Mode	teachers	" It is necessary to maintain the continuity of students' labour practice situation from school to family in order to get good learning results." "Hope to observe and evaluate each stage process of students' problem solving in time." ……
	students	"Hope to get the teacher's timely guidance in the process of labour operation."; " I hope that there will be a platform for finding resources and sharing them with classmates." ; ……
Cognitive Apprenticeship Teaching Mode	teachers	"Provide more learning resources for teachers' teaching."; "Record the teaching and experimental process of teachers."; "Personalized teaching according to the progress information of different students."; ……
	students	"Be able to learn individually according to our own progress."; "Get guidance from teachers in different ways in the process of autonomous learning."; ……
	teachers	"Consider sociality and promote the participation of more stakeholders such as

Interactive Teaching Mode		parents."; ……
	students	"Hope to increase more interesting interactions with my classmates." "Hope my labour achievements can be recorded." ……

Table 2 the interviews' keywords with target users

Prototype 2.0 has made more perfect measures in interactivity, the authenticity of practical situations, and group cooperation, but it still can be improved. In Anchored Instruction Teaching Mode, it is necessary to maintain the continuity of students' labour practice from school to family to keep a collaborative practice situation.

Students hope to have a platform to find learning resources. At the same time, the teacher should strengthen the process guidance. In the Cognitive Apprenticeship Teaching Mode, teachers hope to get teaching resources, record the teaching and experimental process, and realize personalized teaching. Students also hope to learn individually and get guidance from teachers in different ways according to their own progress. In Interactive Teaching Mode, the prototype needs to consider sociality and promote the participation of more stakeholders, such as parents. The students need more interesting interactions with my classmates, and the labour achievements can be recorded.

Prototype 2.0 makes it clear that products ask for higher participation, providing a platform for resources, recording the process, and ensuring that the location does not limit the effect of labour education of students to be more social and sustainable.

Prototype 3.0: the Planting Box equipped with Labour Education Web Version and Applet Version

Prototype 3.0 is improved based on Prototype 2.0's experiential knowledge summary. According to the investigation of the three teaching modes, the existing problems can have common solutions. For example, it is necessary to provide a platform for teachers and students to guide and manage the teaching process. What's more, the acquisition of learning resources, communication with peers, and using the platform to build more stakeholders to participate in the interactive community. It breaks through the limitations of space and venues, continues the labour education practice in schools, and invites parents, students, and labour workers to participate. Create a communication community to realize the sharing of students' labour practice and also improve students' sense of achievement in labour practice through the design of the reward mechanism. The innovation of OMO (Online-Merge-Offline) teaching method, combining offline physical space and online digital space, is about to emerge.

Used in conjunction with planting boxes, a web version of labour education is designed for teachers to support the development of labour courses based on 24 planting boxes. It provides teachers with a platform for acquiring teaching resources, managing the teaching process, and analyzing teaching data, as shown in figure 8 . Students also can freely obtain course resources before taking classes, while teachers can use the platform to show course content and interact with students in the online classroom. Besides, teachers can collect and conduct periodic data analyses on students' labour assignments after class.

For students, an applet version of labour education is designed that is interoperable with the content of the web version, as shown in figure 9. It also expands the number of participants in the labour practice and creates an atmosphere for students to promote labour education between home and school. Students can personalize learning content according to practical topics and their progress and independently query and learn derived knowledge after class by the applet. After the school courses are over, parents can be invited to participate in the after-school practice of labour education. Students can share their homework with the community. Anyone who lands in the community can join in the topic discussion and knowledge sharing of labour education and can make an appointment to participate in the planting of the school roof garden.

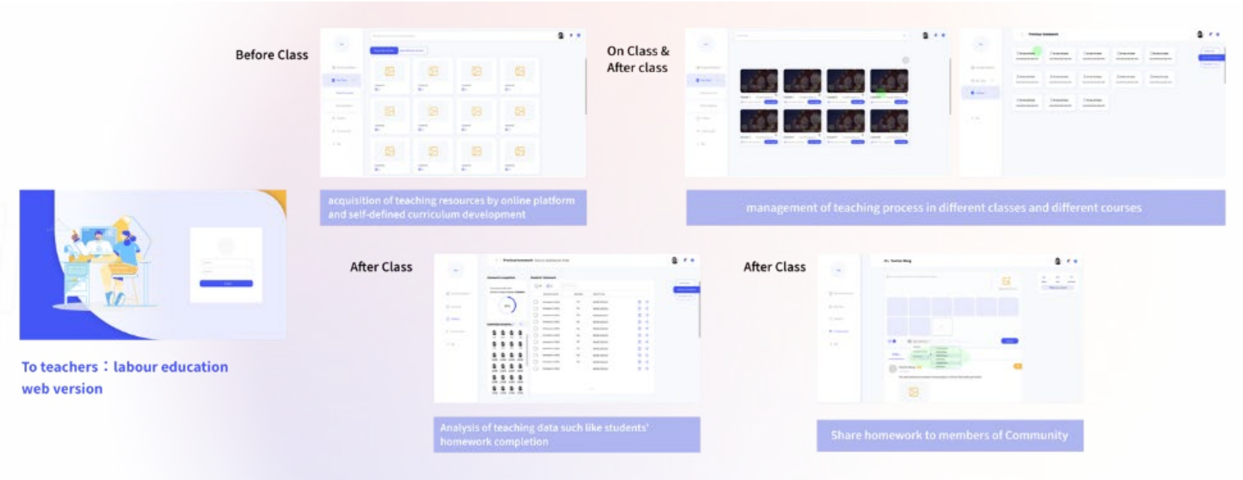


Figure 8 To teachers ：labour education web version

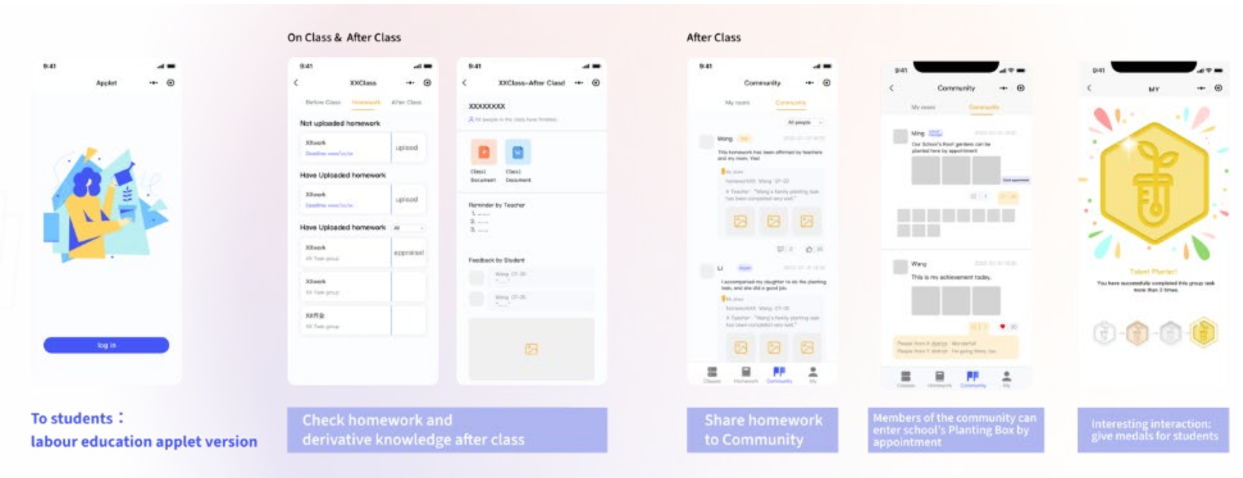


Figure 9 To students ：labour education applet version

Prototype 3.0 uses digital tools to combine online and offline teaching scenarios, develops online courses based on 24 planting boxes, and provides teaching and learning resources to serve the whole process of teachers' labour teaching. And use the online platform to expand the scope of participants so that course learning can continue from school to family and community, increase the interaction between teachers and students, and between students, school and family, and community, and upgrade to a labour education prototype product and service system design.

Conclusion

The prototype design of labour education products explores situational cognitive theory in practical scenes. Based on Chinese labour education's requirements, this paper introduces how we are guided the Situated learning theory to define, ideate and prototype stage of design thinking, and applies the teaching mode of Situated learning theory to test and then upgrade prototype products.

From the Prototype 1.0 product design of "Fish and Vegetable Symbiosis" to the Prototype 2.0 product system design of "Roof Garden Planting Box" to the Prototype 3.0 product service system design of the Roof Garden Planting Box equipped with labour education web version and applet version, labour education has been better transformed from "practice field" to "community of practice". In the practice field created by Prototype 1.0, the situation is authentic. However, some natural conditions in this situation are still simulated, such as the natural water cycle replaced by aquaponics and the natural soil replaced by the nutrient solution. In Prototype 2.0, the products landed from indoor to outdoor through the change of structure and shape, following the real natural environment, and expanding labour education into daily life through Prototype 3.0, breaking the physical space limitation of the practice field and then expanding the field of labour education practice.

In Prototype 1.0, the curriculum practice setting by an integrated product, leads to fewer opportunities for team cooperation in the process of students' practice. Teacher uniformly sets the relevant parameters of the products, so students lack long-term topics of joint exploration and interaction. In Prototype 2.0 and 3.0, the identity of students' team members is from participants to collaborators to managers through modular product prototypes combined with specific group tasks. According to the practice of different modular products in each group and the teaching interaction between teachers with different characteristics, the practice community starts to form according to different goals. The upgrade of Prototype 3.0 promoted labour education to be more social. The situation and participating members of labour practice expanded to families and communities, which increased the practice community members by combining online and offline, and strengthened the interaction and connection of the practice community.

By upgrading Prototype 1.0 to Prototype 3.0, this paper proves the application significance of Situated cognition learning theory in labour education practice and believes that the combination of online and offline teaching methods can effectively promote the formation of practice community and achieve better labour education teaching effect.

References

Brill, J. M. (2001). Situated cognition. Emerging perspectives on learning, teaching, and technology, 50-54.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. 1989, 18(1), 32-42.

Choi, J. I., Hannafin, M. (1995). Situated cognition and learning environments: Roles, structures, and implications for design. Educational technology research and development, 53-69.

Clancey, W. J., Roschelle, J. (1993, September). Situated cognition: how representations are created and given meaning. In Lessons from learning (pp. 231-242).

Crandall, M. (2019). Human-centered design and community engagement. National Civic Review, 108(1), 40-51.

David, H., & Land, S. M. (2000). Theoretical foundations of learning environments. Mahwah, USA.

Dennen, V. P. (2013). Cognitive apprenticeship in educational practice: Research on scaffolding, modeling, mentoring, and coaching as instructional strategies. In Handbook of research on educational communications and technology (pp. 804-819). Routledge.

Duffy, T. M., & Kirkley, J. R. (Eds.). (2003). Learner-centered theory and practice in distance education: Cases from higher education. Routledge.

Hedegaard, M. (1998). Situated learning and cognition: Theoretical learning and cognition. Mind, Culture, and Activity, 5(2), 114-126.

Lim, Y. K., Stolterman, E., Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Transactions on Computer-Human Interaction (TOCHI), 15(2), 1-27.

McLellan, H. (1996). Situated learning: Multiple perspectives. Situated learning perspectives, 5-17.

Nieveen, N., Folmer, E. (2013). Formative evaluation in educational design research. Design Research, 153, 152-169.

Palincsar, A. S. (1989). Debating the situation: A rejoinder to Palincsar and Wineburg. Educational Researcher, 18(4), 5-7.

Plomp, T. (2013). Educational design research: An introduction. Educational design research, 11-50.

Soomro, S. A., Casakin, H., Georgiev, G. V. (2021). Sustainable design and prototyping using digital fabrication tools for education. Sustainability, 13(3), 1196.

Vidulich, M., Dominguez, C., Vogel, E., & McMillan, G. (1994). Situation awareness: Papers and annotated bibliography. ARMSTRONG LAB WRIGHT-PATTERSON AFB OH CREW SYSTEMS DIRECTORATE. 5-15

Li. Q., Zhang. P.P. (2021). Laodong Jiaoyu Shishi Lujing: Jiyu Renzhi Yu Shijian Fenxi [The Implementation Path of Labor Education: Based on Cognitive and Practical Analysis].

Teaching Materials and Education for Primary and Secondary Schools, 11.

Liu.Y., Gao. F. (2010). Qingjing Renzhi Xuexi Lilun Yu Qingjing Renzhi Jiaoxue Moshi Jianxi [Analysis of Situated Cognitive Learning Theory and Situated Cognitive Teaching Model]. Education Exploration, 6, 88-89.

Wang. X.H. (2008). Qingjing Renzhi Lilun Jiqi Zai Jiaoxuezhong De Yingyong [Situated Cognitive Theory and Its Application in Teaching]. Forum on Contemporary Education, 10, 9-11.

Linlin Yang
Linlin Yang is a master student at the College of Design and Innovation at Tongji University. Her major is Design strategy and management and main research is Interdisciplinary innovation in design education, She also does team research focus on Team Learning.

Fei Fan
Fei Fan is a Ph.D. in Management and an associate professor at the College of Design and Innovation at Tongji University. Her research interests are innovative and entrepreneurship education, design innovation and learning design.

Shangjie Zhang
Shangjie Zhang is a master student at the College of Design and Innovation at Tongji University. Her major is Innovation Design and Entrepreneurship, main focuses on the research and innovative design of educational environment & products.

Danqing Meng
Danqing Meng is a master student at the Institute of Higher Education in Tongji University. Her major is Higher Education, and the main research field is design education, she also does team research focused on relative teaching theories.

Ziwen Lu
Ziwen is a master student at the College of Design and Innovation at Tongji University. His major is Innovation Design and Entrepreneurship and main research is learning product design.

Track 9: Research processes and methods 2

- Origins of design choices: retrospective analysis of the resulting prototype of a Research through Design project

- What is Your (Freaking) Problem? Prototypes for problem exploration on early stages of design

- Process as prototype: exploring complex knowledge exchange in the production of low-cost buoyancy aids in Zanzibar through the participatory design of a 'workflow system'

- The prototype-evaluation choreography

Origins of design choices: retrospective analysis of the resulting prototype of a Research through Design project

Audrey Mertens, University of Liège
Çiğdem Yönder, University of Liège
Yaprak Hamarat, University of Liège
Catherine Elsen, University of Liège

Abstract

This paper presents the co-design process implemented throughout a project called "My Architect and I" and the prototypes of tools that emerged from it. These prototypes aim to improve the interactional practices between architects and user-clients in the context of private housing projects in Belgium. The purpose of this study is to identify the roots and triggers shaping the artefacts designed throughout the process. This paper focuses on one of the prototypes brought up by the project. This tool was put together in a short amount of time, under the pressure of the codesign workshops schedule. It results in a paper booklet imagined as a form to be filled in by user-clients in order to inform the architects on their desires and needs. As we take a step back and reflect on the overall outputs from this research through design, we break down each aspect of the booklet to identify the origin of the design choices. This may inform broader design criteria to imagine other tools or strategies to facilitate the interactions between an architect and user-client. This method of deconstructing an artefact is an attempt at objectifying the codesign process' added value. The evolving prototype isn't considered as an end in itself, but rather as a mean to reflect on the facilitation process.

Interactional tool; Codesign; Research through design; Architectural practices; Contact form

Architects too often rely on their own experience as the main reference when designing (Cuff, 1991) and rarely go beyond the brief conversational interaction at the beginning of a project to capture the needs and expectations of their user-client (Norouzi et al., 2015; Van der Linden et al., 2017). This traditional model is now being challenged (Macaire, 2009; Siva & London, 2011; McDonnell & Lloyd, 2014). The involvement of users in this process is essential to the success of the project (Lawson, 2006; Sarkar & Gero, 2017; Arboleda, 2020). A recent systematic literature review highlighted the current struggles these actors still encounter, confirming bottlenecks lying in the architects' assumed roles and in the current expectations and needs of their clients (Mertens *et al.*, 2022a).

Overview of the project "My architect and I"

This research is based on a project called "My Architect and I". The context is that of housing in Wallonia and Brussels, in Belgium, where any construction work affecting the envelope or structure of a building legally requires the services of an architect. Local researchers have shown how that the experience can bring stress and struggles to both architects and user-clients[1] in that process (Nauwelaers & Rossini, 2014; Stals et al., 2016). Based on the assumption that there is an opportunity there for improvement in terms of satisfaction, we address the interactions between these two parties. The primary goal is to identify consequences of this habitus shock (Siva & London, 2009), issues and points of friction, and potential levers for change. The researchers investigate needs and desires that might still not be met in that relationship.

The "My Architect and I" project consists of a two-phase research: (i) a research and preparation phase, and (ii) a codesign process informed by the latter. The second phase can be understood as Research through Design (RtD), "a way of doing research in which design activities play an essential role in the generation of knowledge" (Boon & al., 2020, p.139). In this case, the artefact is not the final target of RtD; knowledge and understanding of interactions remain the main goal pursued (Godin & Zahedi, 2014). Table 1 sums up the phases of the project (also presented in Mertens *et al.*, to be published).

Table 1: Phases and activities of the project

Research and preparation phase (i)	Systematic literature reviews (SLR)	SLR conducted on interactions between architects and user-clients during housing design processes (Mertens *et al.*, 2022a)
		SLR conducted on matters of knowledge in codesign and their methodological implications (Yönder *et al.*, [to be published]a)
	Interviews	15 interviews with architects
		14 interviews with user-clients
		17 interviews with designers
	Planning & designing the workshops	4 researchers, three team sessions to design the codesign process itself
Codesign process (ii)	Restitution & Sharing (1)	A two-hour long online workshop;16 architects, 8 user-clients. Goal: share insights gathered from interviews
	Ideation & Design (2)	5 face-to-face workshops in 4 different cities in Belgium (5x2h). Total of 12 architects (including representatives of the local association of architects) and 9 user-clients
	Tests of the prototypes & Iterations (3)	(a) 4 tests with 4 tool prototypes during a public event; 4x1h; a total of 21 architects (including students, academics, representatives of the local association of architect and professionals from the construction industry), 8 user-clients
		(b) 2 tests with 2 tool prototypes in architectural agencies; 2x1,5h; 4 architects and 2 user-clients
		(c) Test in a design conference; 1,5h; 8 designers/researchers (Mertens *et al.*, 2022b)

(i) To construct a better understanding of the field, we conduct: systematic literature reviews; interviews with architects (n=15); with user-clients with an experience of interaction with architects for a private housing project (n=14); and designers practising human-centred design or codesign (n=17). Further detail on that phase of the research can be found in the specific papers written by the authors (for instance: Mertens *et al.*, 2022a; Yönder *et al.*, [to be published]a).

[1] In this paper, as we focus on private housing projects, the clients and end-users of the building coincide. Therefore, we use the term "user-client".

(ii) The co-design process consists of a series of workshops of three types: (1) Restitution & Sharing; (2) Ideation & Design; (3) Tests of the prototypes & Iterations. The aspiration pursued is to develop some tools to help architects and user-clients facilitate interactions throughout private housing designs. Intrigued readers can find further details of these workshops in specific papers by the same authors (for instance: Mertens *et al.*, to be published).

The whole workshop series is designed by the team of researchers (n=4) prior to the launching. Some workshops build on the content of a previous workshop. In between sessions, meetings are held in order for the researchers to make sense of the data collected and inject the results of this analysis in the next phase, much as practising designers would.

(1) The first workshop, hosting 16 architects and 8 user-clients, consists in a two-hours online audiovisual exhibit (January 2022). The journey presented broadcasts insights extracted from the interviews, organized in ten chapters to sensitise the participants and build empathy between the two parties. At the end of this session, participants select what they consider to be the most pressing challenge regarding interactions between architects and user-clients (amongst 12 themes put together by the research team based on phase 1's data). Top rated challenges are then refined by the researchers to be used in the next series of workshops (e.g. (2) Ideation & Design).

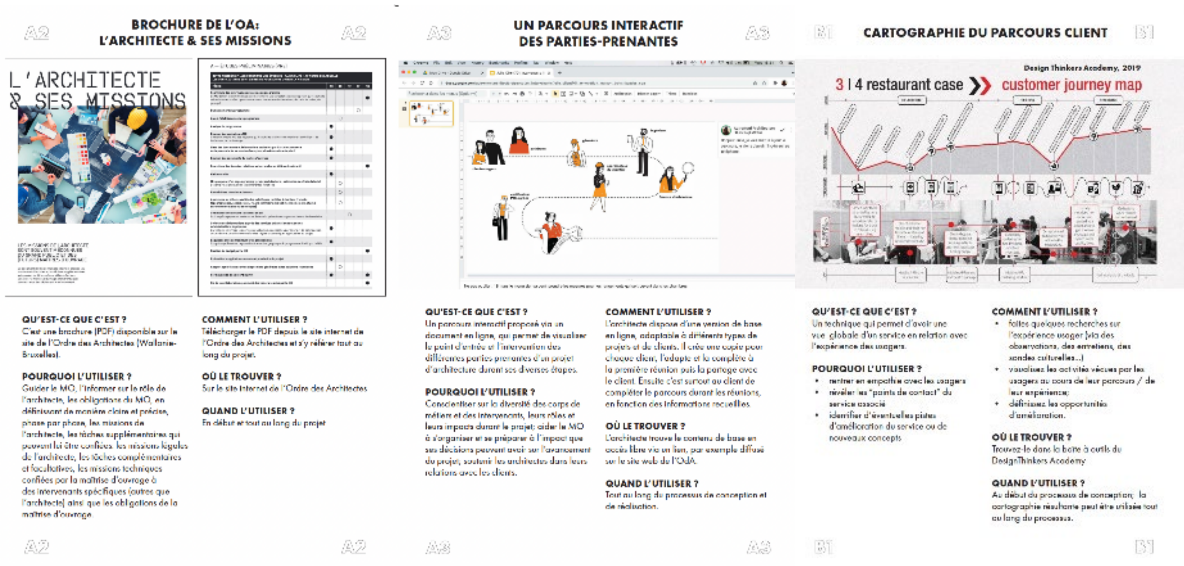


Figure 1: Examples of the inspirational TTSM cards given to the participants during the Ideation & Design activities (2)

(2) The second type of workshop (spring of 2022) consists of five workshops held for about two hours each. These workshops take place in various locations in Belgium (Brussels, Liège (n=2), Namur and Arlon). Altogether, 11 architects, 9 client-users and 1 representative of the *Order of Architects* participated in 8 mixed groups. Participants are invited to adapt, revisit and develop a tool based on inspirational tools, techniques, strategies and methods (TTSM) cards used as probes (also referred to as "provotypes" in Mertens *et al.*, to be published) or to develop a brand-new concept. These cards (Figure 1) introduce and

describe tools extracted from a grey literature benchmark[2], from the interviews conducted with the designers (cf. phase 1 (i)) and from an inhouse brainstorm session organised by the researchers. These provotypes “evoke a focused discussion in a team”, being “on the table” (Sanders and Stappers, 2014).

The artefacts cocreated by architects and user-clients result in “pretotypes” of the tools, imagined to facilitate architect/user-client relationships.

An in-between task completed by the researchers consists of merging the results into four tools (version α) as a synthesis of the eight groups’ “pretotypes”. These tools are presented to two architects for a unique feedback session to help shape a realistic prototype for the following steps (version β) (see Fig.2).

(3) Tests of these prototypes are then conducted to obtain feedback and iterate/develop them further. Three types of testing sessions are organised: (a) during a public event (conference + testing sessions) at the University of Liege, Belgium, in small groups (4 sessions with 29 participants: architects, architecture students, user-clients or curious citizens, and representatives of the Order of Architects); (b) in architectural practices by practitioners architects and clients (2 tests, 4 architects, 2 client-users); (c) at a design conference (2 prototypes tested by 8 designers and/or design researchers, (Mertens *et al.*, 2022b).

These tests are based on role-playing games through which participants – impersonating architects and user-clients - improvise a first meeting. This method is inspired by design fiction (Sanders and Stappers, 2014), to help participants envision a possible change in their routine practices and enable to test and obtain feedback rapidly on the prototypes.

The two architectural agencies in the test (b) are presented with all four prototypes (versions β) and are asked to pick which tool they would like to test. The results of this session are implemented and lead to the prototypes of two tools (version δ).

Focus and Approach

This paper focuses on one of the tool prototypes (version δ) developed during the codesign process, i.e. a paper booklet imagined as a form to be filled in by a user-client, mainly in order to inform the architect about his/her desires and needs. An updated pdf version of this tool can be found on Inter’Act Lab’s website (Inter’act, n.d.). The other tool selected for the (version δ) prototyping is presented in another paper (Yönder *et al.*, [to be published]b).

Analysis conducted in between workshops are design-driven – quick and pragmatic – alike a design practitioner’s. The purpose of this paper is to take a step back and reflect on a

---

[2] Collection of data outsourced: 40h paid mission, carried out by a master student. Job description: identify existing tools and strategies in the field of "architect-client relations / structuring of the architectural mission", from "grey literature" (i.e. non-scientific publications, websites; YouTube channels; etc.). The main goal is to create a "database" of existing tools, as well as a small reading grid (excel type) with a mini summary of a few lines for each tool. This research is conducted in French and English, both locally and internationally and results in a list of 85 tools. This database is browsed by the first author of this paper, revising all the tools and strategies, who then retrieves a relevant selection - in regard to the challenges raised in the first workshop (1) - for the inspirational TTSM cards to be used in the workshops (2).

prototype and deconstruct it, a posteriori, in a research-driven approach. As we take a step back and reflect on the overall outputs of this research through design, we break down each aspect of the booklet to identify the origin and targeted outcome of the design choices.

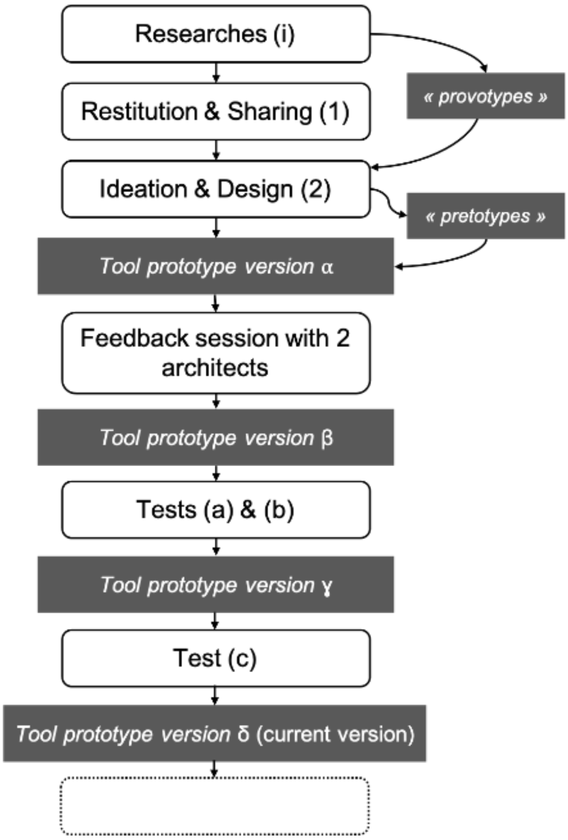


Figure 2: versions of the prototype in regard of the tests

We question the elements of the process that nourishes the current prototype (version δ). In order to deconstruct and analyse it, the booklet's content and characteristics are broken down step by step: its base concepts, materiality, chapters, and contents. For each of these elements, we look back on the process to find its origin and purpose.

Findings

This paper booklet prototype is based on an archetypal tool found in the grey literature, developed by Donnell and Day Architecture (2020).

The tool is a pdf booklet, downloadable on the website of the architects. It is a guide, namely "How to write a brief for an architect" that can be used as a template for the user-client to fill in and to brief an architect for a project, as well as inform themselves on important aspects of the process. The New Zealand architectural firm presents their "Ebook" as a way to facilitate communication to the architects "the core goals of what [they] want to achieve in [their] new build or renovation, in the unique way that you love to live life". They also promote it as a way to "learn how to summarise [their] vision and mission statement for the build, record (…) functional brief in the editable PDF form included, manage budgets, dreams and design expectations, and understand how to work collaboratively with your Architect to achieve your goals" (Donnell and Day Architecture, 2020). These are challenges that have been brought up in phase (i) of our research, highlighting this tool as particularly relevant as a baseline to reflect on and adapt. Bogers *et al.*'s (2008) recommendations are beared in mind to develop the tool (versions α and β) in-between the workshops (2) and the tests (3): making priorities and essence of the project explicit, as for the requirements, and including qualitative information about the user-clients' needs on top of quantitative requirements. According to the authors, "figures about square meters, temperature levels, etc, are important, but they tell a very limited story about the accommodation needs of the client", recommending to encourage the user-clients to share "culture, attitudes, ambitions and desires, activities and business processes, scenarios and forecasts for the development of the business, and the "feel" for the project" (Bogers *et al.*, 2008, p.115). The briefing process, among the most essential parts of the design stages (Bogers et al., 2008; Côté et al, 2009; Hershberger, 2015), should identify "values, goals, facts, and needs" (Hershberger, 2015, p.336) and could help diminish cost overrun due to design mistakes (Côté et al., 2009).

This literature, together with the data collected throughout both phases of the project (i) & (ii), is embedded in the latest version of the tool (version δ). The tool manifests as a synthesis of several design criteria raised over time during the whole process. The table below displays the characteristics and contents of the booklet, analysed point by point, chapter by chapter, and identifies their provenance and aim.

Table 2: Analysis of the content and characteristics of the booklet prototype

	Content	Origin & purpose
Concept	Contact form / Brief template for specific private dwelling projects	The systematic literature review (Mertens *et al.*, 2022a), particularly Bogers *et al.*'s work (2008). Grey literature (Donnell and Day Architecture, 2020), inspirational TTSM card selected by 1 of the tables during the (2) Ideation & Design activities. Testimonies from architects throughout interviews and workshops converge, highlighting the fact that architects are already overworked and have no time to spend on yet another tool. This supports the choice of a user-client led tool to fill in.
Materiality	Paper	Five tables (out of eight) during the (2) Ideation & Design discussed a paper support option vs. the numeric version, through an app or an online form. Three of these tables reveal a need for an easily "carry-on" type of tool, converging with insights gathered during the interviews (research phase i).
Visual aspect	Colours and typo	Based on the lab's graphic charter for consistency of the tools, considered as a toolkit. The δ version of the tool is visually linked to the research lab. Customization by the architectural offices has been raised and debated. We settle on a non-customised artefact, visually identified as a third party's (Inter'Act's, neither architects' nor user-clients').
Front page	Title of the tool & contact information of the user-clients	Thought as a way to make things very simple and clear for user-clients, as their testimonies (in both the interviews and the workshops) point out that they are

		often overwhelmed with documents that are not user-friendly. The contact information aims for the architects collecting the booklet to gain time in their note taking regarding the users, thus in their overall briefing process.
Page 2	Chapter including an explanation of why the user-client needs an architect, his/her role and expertise. Link for more information on the web.	Originates from the interviews with users and architects, showing a lack of understanding of the architect's role. This problem is validated by the co-design participants as a major problem.
Page 3	Chapter: Guide for the first steps	Based on user-client testimonies during the interviews, confirmed and developed by several user-clients during the workshops (2): user-clients feel left to their own devices, very lost at the beginning of the process, not knowing where to start, what they are expected to do or what can be expected from an architect.
Pages 4-9	Chapter aiming for all the future occupants of the project to be presented; for desires, dreams, tastes of the participants to unfold. Six pages left almost empty, with just a few sentences to help ideas emerge (questions about their ways of living, habits, hobbies, dreams, future…)	This section is based on two success stories encountered in the interviews during phase (i): the suggestion of a blank A3 page left by one of the architects on the clients' kitchen counter, as a way for them to doodle, annotate and suggest ideas to the architect; and user-clients spontaneously creating a visual presentation of their family with enough detail for the architect to really capture all the requirements for the project. It is further developed during the feedback session with the two architects. It is particularly appreciated during the tests. Feedback during several tests points out the need for a lot of space for the client-users to express themselves (drawings, collage, text…) and present several profiles of a single family, for instance.
Page 10	Chapter: "Priorities"	Raised by architects in the interviews and further discussed during the three phases of the workshops, as both parties often fail to align their preoccupations. User-clients tend to forget to mention what matters the most to them and the architects sometimes fail to meet crucial demands because they do not consider some things as priority. Architects keep in mind technical priorities to ensure the project to follow through, whereas user-clients are often unaware of these details. This also stirs up discussions about what the architect has to consider as essential for the good execution of the project, and what he/she might have to discard if the budget doesn't allow to realistically meet all the expectations of the user-clients.
Page 11	Chapter: "Fears & Budget"	This is a major challenge brought up by the research phase (i), voted for during the first workshop (1) as essential and developed during the following workshops. This chapter aims to open the discussion about taboos

		that often bring frustration between architects and user-clients.
Pages 12 & 13	Chapter: “Expected program”	Aiming to gain time for overworked architects (cfr. interviews and codesign process) while insisting on the fact that this might still evolve and could also have to be downsized if not realistic in regard to the budget.
Pages 14 & 15	FAQ and explanations	Answering the issues due to misunderstandings at the beginning of a project, raised mainly during the interviews (similarly to the origin of the page-3 Chapter: Guide for the first steps)
Pages 16 & 17	« Questions you want to ask your architect » notebook page, mainly blank	Interviews and workshop testimonies raised the fact that user-clients often have a list of questions they want to raise and discuss with their architect. Tests highlight the need for space for the user-clients to write down their concerns.
Pages 18 & 19	Another notebook page mainly blank (left page lined, right page blank page) Details of the funds that supported the research that led to the booklet, and disclaimer highlighting the fact that the booklet is not a legal document but a support document	Tests (particularly the (b) test) highlighted the need for space for the architect to take additional notes (text and sketches) throughout the conversation with the user-clients, adding up on the information contained in the booklet. The issue of the booklet as an informal document was raised during the workshops and tests: architects want it to be clear that the booklet is not a legal document and that they might not be able to answer every demand requested by clients in the booklet. The booklet is to be considered as an aide to facilitate conversation and keep track of the desires of the user-clients, help them navigate the overwhelming and complex launch of a project.
Back page	Logos and space left blank	Tests (particularly the (b) test) highlighted the need for space for the architect to take additional notes (text and sketches) throughout the conversation, the back of the booklet being very convenient to do so.

This tool retains the researchers’ attention as it echoes Bogers *et al.*’s conclusions, arguing that “to improve the everyday practice of briefing, it is important to realize that architects cannot produce a good design, when clients fail to be clear about what they want” (2008, p.115). This booklet concept is hardly innovative but it answers multiple challenges brought up through the research phase and testimonies shared by the participants during the codesign process as well. This low-tech tool enables easy implementation of multiple solutions to facilitate communication between architects and user-clients upon various identified friction points.

The main limit of this paper lies in the fact that we do not track the elements that have been abandoned in previous versions of the prototype. We rather focus on content validated throughout the tests.

Discussion

This paper considers the artefact as a way to look back on the process. Deconstructing the prototype retrospectively aims to understand its essential components, their purpose and their origin(s). This method, inspired by retro-engineering, enables us to evaluate the various phases of the Research-through-design project; how those phases impacted the artefact and to track down the researchers' choices.

This work (i) helps better understand how choices are combined together to generate an artefact throughout such a codesign process; (ii) raises the question of how each profile contributes, in a complementary way, to the process (both designers and non-designers, as well as researchers); (iii) increases a critical and objectified glaze of such codesign processes, pinpointing actual key moments springing positive effects; (iv) and therefore demonstrates the concrete added values of codesign. This "deconstruction" is a method in itself that the researcher would like to replicate on other projects, which could perhaps ultimately lead to a model for the evaluation of processes such as codesign.

Once the content is broken down, the origin and purpose of each section can be looked up and heightened. This highlights the importance of the research phase and the elaboration of the workshops, especially the interviews and development of the inspirational TTSM cards that set the ground to numerous elements constituting the booklet. However, it is mainly the workshop sessions that validate the concerns brought up in the research phase and confirm the most pressing content the tool should hold. The test brought up a few simplifications, space requirements for an ergonomic use of the tool, and re-phrasing of some of the content. However, the changes or additions were rather limited to subtle refinements.

We want to insist on the primary purpose of RtD which is to produce knowledge and understanding (Godin & Zahedi, 2014). In this specific project, there are no deadlines nor final product expected by the funding agency. This allows the created artefact to evolve and not clot. The understanding of the interactional practices between actors will extensively be developed in other papers by the same authors.

However, this paper highlights the added value of the artefact itself. Even if pursued as an additional bonus or “side-effect” in parallel to the research, we believe the prototype could be very useful to support architectural practice. This tool can help empower user-clients and bring them a step closer to being co-creators in the design process, as they are already considered experts on use and on their own ways of living, learning, working, etc. (Sanders and Stappers, 2008).

Moreover, participants are reaching out to have access to this tool (Mertens *et al.*, to be published). Therefore, they are now accessible online so participants and the general public can benefit from them.

To further iterate on the tool, it is now essential to confront it with real-life conditions. The question arises as to the method. Several options are considered: (i) observe and monitor (without taking part in the action) the use of the prototype; (ii) identify agencies willing to use the tool but without interfering/observing, and conduct feedback interviews with end-users (architects and their user-clients) *a posteriori;* (iii) return (as first author) to professional architectural practice in the years to come and test the tool first-hand. This may be an opportunity to continue the research through use in action, equipped with prototypes developed in the research as a toolkit.

This last point raises the question of finality: a prototype developed in RtD is potentially never "done" and delivered. This last round of tests could be a means to iterate to reach an improved version of the prototype. But the research team could also let go of the ownership of the artefact, accepting and encouraging end-users to take hold of their own versions of the tool as they see fit. In this last scenario, ideally, researchers would perhaps observe and document its organic evolution.

Conclusion

This paper is an attempt at deconstructing the artefact resulting from a codesign process. Probes inspired by scientific and grey literature were adapted by participants (architects and user-clients) and researchers to the concerns and struggles specific to the design of architectural dwellings in Belgium.

The latest version of the prototype consists of a booklet to support user-clients in the initial phases of their private housing project, specifically during the first contact with an architect and through the formulation of a brief. We advocate that a well-supported briefing process can prevent further struggles in the following stages of the design and construction processes.

The results may also inform broader design criteria and enrich other tools or strategies aiming to facilitate the interactions between an architect and user-client. The evolving prototype isn't considered as a finished product, but rather as a base to reflect on the needs in terms of facilitation, and as a still-evolving template for architects, designers and client-users to build on and take ownership of. At last, this method of deconstructing an artefact helps objectify the codesign process' added value and could be replicated and expanded to other cases.

References

Arboleda, G. (2020). Beyond participation: rethinking social design, Journal of Architectural Education, 74 (1), 15-25.

Bogers, T., van Meel, J. J., & van der Voordt, T. J. (2008). Architects about briefing: Recommendations to improve communication between clients and architects. Facilities.

Boon, B., Baha, E., Singh, A., Wegener, F. E., Rozendaal, M. C., & Stappers, P. J. (2020). Grappling with diversity in research through design*.*

Côté, P., Goulette, J. P., & Marques, S. (2009). Programmation architecturale et architecture virtuelle. Intermédialités, (13), 77-88.

Cuff, D. (1991). Architecture: the story of practice*, Cambridge: MIT Press*

Donnell and Day Architecture (2020). How to write a brief for an architect. Retrieved from: https://www.donnellday.co.nz/thoughts/how-to-write-a-brief-for-an-architect-pdf-download/

on the 5/01/23.

Godin, D., and Zahedi, M. (2014) Aspects of Research through Design: A Literature Review, in Lim, Y., Niedderer, K., Redströ m, J., Stolterman, E. and Valtonen, A. (eds.), Design's Big Debates - DRS International Conference 2014, 16-19 June, Umeå , Sweden.

Hershberger, R. (2015). Architectural programming and predesign manager*. Routledge.*

Inter'Act Lab (n.d.). www.interact.uliege.be

Lawson, B. (2006). How Designers Think: the Design Process Demystified*, Routledge, London.*

Macaire, E. (2009). Des architectes à l'épreuve de la participation. In F. De Coninck et J.-F. Deroubaix (Eds)., Ville éphémère, ville durable – Nouveaux usages, nouveaux pouvoirs*, Paris: Édition L'Oeil d'Or, 135-147.*

McDonnell, J., & Lloyd, P. (2014). Beyond specification: A study of architect and client interaction. Design Studies, 35(4), 327-52.

Menichinelli, M. (2020). Exploring the impact of Maker initiatives on cities and regions with research through design approach. Strategic Design Research Journal, 13(01), 92-109.

Mertens, A., Hamarat, Y., & Elsen, C. (2022a). Interactions between architects and end-users during housing design processes: a systematic literature review. Archnet-IJAR: International Journal of Architectural Research.

Mertens, A. , Yönder, C.* , Elsen, C., & Hamarat, Y. (28 June 2022b).* My Architect and I: A role-playing workshop to improve housing design service. *Presented at DRS2022, Bilbao, Spain. *These authors contributed equally to the work.*

Mertens, A., Yönder*, Ç., Hamarat, Y., & Elsen, C. (to be published). Transformative Effects of Co-Design: The Case of The "My Architect And I" Project. *These authors contributed equally to the work.*

Nauwelaers, I. & Rossini, C. (2014). Construire, une brique dans le ventre pas toujours digeste. Magazine Test-Achats, 584, 10-16.

Norouzi, N., Shabak, M., Embi, M.R.B. and Khan, T.H. (2015). The architect, the client and effective communication in architectural design practice, Procedia - Social and Behavioral Sciences, 172, 635-642.

Sanders, E. B. N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. Co-design, 4(1), 5-18.

Sanders, E. B. N., & Stappers, P. J. (2014). Probes, toolkits and prototypes: three approaches to making in codesigning. CoDesign, 10(1), 5-14.

Sarkar, S., & Gero, J. S. (2017). The topology of social influence and the dynamics of design product adoption. In Design Computing and Cognition'16 (pp. 653-665). Springer, Cham.

Siva, J., & London, K. (2009). Architects and their clients: Relationship analysis using habitus theory. International Journal of Interdisciplinary Social Sciences, 4(3), 131-146.

Siva, J. & London, K. (2011). Investigating the role of client learning for successful architect-client relationships on private single dwelling projects. Architectural Engineering and Design

Management, 7(3), 177-189.

Stals, A., Jancart, S., & Elsen, C. (2016). How do small and medium architectural firms deal with architectural complexity? A look into digital practices. In eCAADe 2016-Education and research in Computer Aided Architectural Design in Europe, 34th Annual Conference.

Van der Linden, V., Dong, H. and Heylighen, A. (2017). "The good client: how architect-client dynamics mediate attention to users", Conference Proceedings - Professional Practices in the Built Environment, 174-183.

Yönder, Ç., Hamarat, Y. and Elsen, C. ([to be published]a). Matters of knowledge in co-design and their methodological implications.

Yönder, Ç., Mertens, A., Hamarat, Y. and Elsen, C. ([to be published]b). Re-imagining knowledge sharing in and about architectural services through a multilayered journey map tool.

Audrey Mertens

Audrey holds an MS degree in Architectural Engineering from ULiège. After some field experience in architectural agencies, she takes a step back from the profession as a Ph.D. student, studying the interactions between architects and their end-users.

Çiğdem Yönder

Çiğdem Yönder is a designer and researcher holding a MA in Interior Architecture and Environmental Design from Hacettepe University. She focuses on collaborative and participatory design and creation processes. Currently, she is pursuing her Ph.D. at ULiège as a researcher of Inter'Act Lab.

Yaprak Hamarat

Yaprak's works unfold in two intertwined axes: pragmatic aesthetics and social design, both driven by ethnographic fieldwork and research through design. Through a politico-anthropological approach, her research and practice investigate the engagement between humans and non-humans for the ecological transition of the artificial.

Catherine Elsen

Catherine Elsen is Professor at University of Liège and former Research Affiliate at MIT. She holds a Ph.D. in Engineering Sciences and MS degrees in Social Sciences and Architectural Engineering. Her research interests cover design processes and the impact tools and methods have on such processes.

What is Your (Freaking) Problem?
Prototypes for problem exploration on early stages of design

Juan Ruiz, Linköping University, Sweden.
Renee Wever, Linköping University, Sweden.

Abstract

Prototyping is a crucial element of the design activity. Prototypes serve as temporary and incomplete embodiments of design ideas with which designers explore the design problem as well as propose and refine possible solutions to the problem. Given its deep connection to solutions, prototyping has been typically associated with the later stages of design. A stage in which the problem has been sufficiently mapped that a solution can be proposed and refined based on the discovery of requirements. Yet the question of what it means to prototype for problem exploration remains. To provide an answer to this question, first we take a quick look at what the role of prototypes is in design and more specifically what their role might be in the early stages of design. And later we discuss from the perspective of the reflective conversation that the designer has with the artifact it has created and what we reflect on when dealing with problem exploration. Subsequently some illustrative examples are presented of unintentional problem exploration prototyping from student design projects. To conclude, a reflection of the importance of design education in preparing practitioners to better deal with different types of prototyping beyond solution refinement.

Problem-space; early design; problem-oriented prototyping; design education; prototype

The process of design problem-solving has been characterized and distinguished from other problem-solving processes, based on the type of problems it aims to solve and by the way design practitioners go about solving said problems. The kind of problems that designers deal with are often ill-defined (Archer, 1979; Buchanan, 1992; Cross, 1982). Ill-defined problems are problems that in their early stages lack definition, in which all the elements that make up the problem are not yet known and in which part of the problem-solving effort is to explore the problem itself, to attempt to provide it with enough definition that would enable the problem solver to propose solutions.

The way in which designers tackle ill-defined problems involves the simultaneous exploration of both the problem and possible solutions by creating temporary solutions that allow to uncover and redefine elements of the problem while experimenting with possible solutions (Cross, 1982; Lawson, 2006; J. Ruiz, 2020). These temporary solutions are known as prototypes.

The creation and utilization of prototypes as a means to explore the design space of problems and solutions is then at the heart of the design practice. Prototypes function as tools that allows designers to propose possible temporary, perhaps even “disposable”, solutions with the aim to test, explore and/or gain new knowledge that allows the production of a desirable final solution. Because of their intrinsic value to the design problem-solving process, prototypes have received attention from design researchers and many aspects of creation and classifications of prototypes

have been studied. Aspects such as the process of prototype creation and their relation to materials and techniques used, levels of refinement and definition, so-called fidelity (Rudd et al., 1996; Virzi, 1989; Virzi et al., 1996), the roles of prototypes (Menold et al., 2017; Ulrich et al., 2008), prototyping strategies (Camburn et al., 2017; Domingo et al., 2020; Houde & Hill, 1997; Menold et al., 2017), etc. Among them we can also find the aspect of timing (Camburn et al., 2017) which refers to when in the process of design prototypes are created and used.
Given the nature of prototypes as representation of possible solutions, even if only temporary, they are deeply connected with the later stages of the design and engineering process. This means that a lot of the attention given to prototyping is more closely related to prototypes as embodiments of explorations of solutions, and in a stage in which the design problem should be “less” ill-defined and more aspects of the problem should have been uncovered. However, studies have shown the importance of prototyping in the early stages of design (Camburn et al., 2017; Rothenberg, 1991; Virzi, 1989) and several authors refer to prototypes as objects of active learning or exploration, yet not much has been shown in the literature of how this might happen. This then leads us to the question of *what does it mean to prototype with the (sole) purpose of problem exploration in the early stages of design?*

What do Prototypes do & Role of prototyping

The creation and use of prototypes is an activity that is not exclusive to design. Prototypes are used in many engineering disciplines as well as in informatic disciplines. It is not uncommon to see the term being used to describe artifacts or processes that spam from software development all the way to showcasing conceptual futuristic products, which highlights how field dependent our understanding of prototypes is. This wide range of usages of the term prototype means that the concept has many possible descriptions and definitions, based on where and for what the term is being used. For these reasons, we will not attempt to present a definition of what prototypes are, but rather discuss what prototypes do and what their role is in understanding design problems in the early stage of design.

If we review prototype/prototyping literature and the many definitions provided, we can discern what prototypes do, and what is the role they play in the design process. One of the primary functions of a prototype is that of serving as an embodiment, regardless of shape or medium either physical or virtual, of a design idea with the intention of providing the designer a means to expand their understanding of the design space (BenMahmoud-Jouini & Midler, 2020; Camburn et al., 2017; Houde & Hill, 1997; Lande & Leifer, 2009; Menold et al., 2017; Ulrich et al., 2008). From this we can already start to see certain key elements about the prototyping act and the artifacts created through it that can help us then examine the question of prototyping for problem exploration.

Embodiments of ideas

The first part, and perhaps the one that has been explored the most in the literature, is that of prototypes as embodiments of design ideas. The extensive exploration of idea embodiment can provide us some clarity on the different ways or methods of representing ideas (BenMahmoud-Jouini & Midler, 2020; Camburn et al., 2017; Pei et al., 2011) the technologies that could be utilized to create them, as well as their level of detail or fidelity among other important aspects of the artifacts we create as prototypes.

Yet the question posed by Houde and Hill (1997, p. 368) “is a brick a prototype?” and its subsequent answer “depend on how it is used” reminds us of two crucial aspects of prototyping. Firstly, that an over-emphasis on the prototype itself can create a fixation to think more about the artifact rather than on the objective for which we have created it. Which in turn could lead to over-design and over-trust on the prototype artifact (BenMahmoud-Jouini & Midler, 2020). And secondly, that however important the embodiment of design ideas is, what questions we ask of our prototypes and the answers or learnings we extract from them are of the outmost importance (ibid).

Means of exploration

The second part that we can then examine is that of prototypes providing the means of expanding the understanding of the design space, which is deeply related to the roles or objectives that prototypes have in design problem-solving process. An important part of design work is to be able to use design tools, such as prototypes, to better understand what are the different important elements that make a situation problematic. This could mean an exploration of what are pain points, challenges, needs, or desires that must be addressed and what possible solution, or combination of solutions, can be better suited to solve this problematic situation. This is often done in an environment of collaborative work, with other design practitioners, people from different professional backgrounds, potential users, and clients.

Given how wide the range of explorative actions is that designers need to address, prototypes become fluid objects that could serve multiple purposes. If we look at multiple examples from prototyping in the literature, we can find multiple characterizations or divisions of prototype roles.

Ulrich, Eppinger & Yang (2008) propose a two-sided approach. Firstly, by proposing a two-by-two matrix of type of prototypes which in its first axis has a dimension of physical vs analytical prototypes and on the second axis a dimension of comprehensive vs focused. And secondly a division of prototypes by their purpose which is divided in four: learning, communication, integration, and milestones.

In Camburn, et al.’s (2017) review of prototyping literature, they identify four distinctive objectives: Gradual *Refinement* of design solutions, *Exploration* of new design concepts, Tools of *Communication* between different stakeholders, and for the process of *Active Learning* and gaining new knowledge.

Menold et al. (2017) propose a framework of prototypes that draws from human-centered design methodologies to subdivide prototyping into three different categories: Prototypes for desirability or the appeal of certain solution to the users, prototypes for feasibility or technical possibility of the solution to work, and prototypes for viability or the likelihood of a solution to be profitable and a sound business option.

Benmahmoud-Jouini and Midler (2020) go even further to present three archetypes of prototypes*, stimulators, demonstrators,* and *validators*, with the intention of presenting an overarching set of characteristics that go beyond a simple individual role.

Yet, from the previous examples, we can observe that very little separation is being made in terms of different objectives of prototypes based on which stage of the design process are the prototypes being used. As shown in Camburn et al.'s (2017) review, a great majority of literature mainly focuses on solution refinement which is connected to final stages of design process that extends to the other studies here presented. Along with some of the other categories of prototype roles and objectives that are of vital importance to the entire design process and not to one specific stage. Leaving only very few that mainly focus on early stages of design and none with the specific objective of prototyping for problem exploration which is rather treated as a possible consequence of prototyping.

One thing can be discerned from these different categorizations of prototyping and how they are used that lead into the reason for exploring problem-oriented prototypes of this paper. From the previous authors we can separate prototyping from different perspectives into two distinctive areas, prototyping for solving a problem and prototyping for testing of a solution. From this we can propose a third area, to be further explored in prototyping research, of prototyping for discovery and learning of the different possible variables of the problem to be solved (Figure 1).

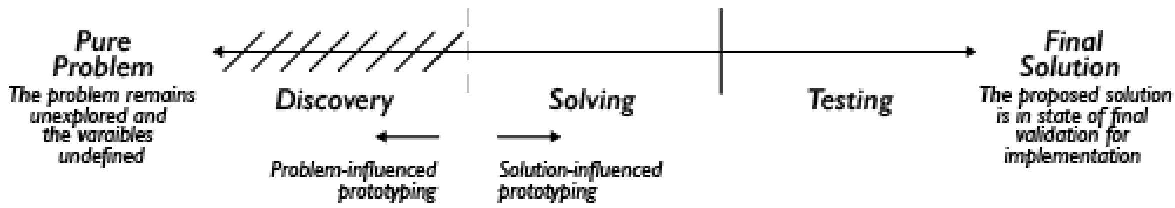


Figure 1. Prototyping for discovery

Some prototyping techniques, like Lego prototypes of services, can be and are being used to also explore current situations. In such a case, the Lego representation could be seen as a discovery process, but it is likely to result in a hybrid activity both identifying potential problems and proposing solutions. Hence, the prototyping technique and activity are not exclusively focused on exploring the problem. In other fields of design, such as critical design, the whole purpose may be to expose a problem (as one example, Anna Odell's project *Undersökningen*, in which she invited influential men to experience the denigrating experience of sitting in a gynecology chair undergoing an examination, comes to mind). But here the object that questions or exposes said problem is a final design, and not a prototype. Hence, we are not claiming that what we propose is entirely new. Yet what we aim to explore in this paper is what it would mean to develop prototypes in the early stages of a process, that in the end is aimed at yielding some kind of solution later on, but where the initial prototyping efforts have the sole purpose of exploring (some aspects of) the problem.

Prototyping in early stages of design

Early-stages of design

Design projects can have a wide range of starting points based on the level of advancement of the design brief and the designated starting point of the project. There are many degrees in variability in terms of known and unknown information that designers would deal with at the starting point (Ruiz, 2020).

Several seminal authors within design offer a distinction in between two types of design activity. Firstly, design activity in which a lot of the variables and constraints of the design space are known to the designer and their job is to find the best combination of elements that address these variables to produce a solution. And secondly, design activity in which a lot of information is conflicting or unavailable to the designer at the starting point, and before a solution can be produced, the designer's job is to provide the space with more clarity and understanding of what the problems, goals, limitations, and criteria to possible solutions are. Simon (1973) refers to this as well-define and ill-define problems, Gero (1990) refers to them as routine and non-routine design, while Buchanan (1992) refers to them as determinate and wicked problems.

For the focus of this paper, we mainly refer to the second set of problems. The kind of design problems in which the designer spends a great deal of time in the early stages of the design process to provide structure to the problem (Simon, 1973; Voss, 2005). Through establishing a problem space area by determining what are possible users and stakeholders, what needs, and problems do these users face, what are acceptable criteria for a sensible solution and what are possible limitations and constrains that need to be considered (Goel & Pirolli, 1992; Simon, 1973; Smy et al., 2016).

One of the main reasons for this paper is the behavior observed in classroom of our design projects course. The course is based on design thinking methodology and grounded in challenge-based learning, experiential learning, and iterative models of design for problem solving. In it, groups of students are selected and assigned to real industry projects provided by an industrial partner. Over the course of nine months, students follow a methodological process of simultaneous problem and solution exploration through the use of ethnographic studies and prototype development that follow design thinking iterative process (Domingo et al., 2020; J. Ruiz, 2020; J. F. Ruiz & Wever, 2022). One of the difficulties that students face during the first missions of the project is to produce prototypes that are not intended as fully fleshed solutions but rather as problem probing and exploration.

Prototype-based reflection in action

In 1983, Donald Schön proposed that, in the practice of design, this behavior of searching for creative solutions is one of reflection-in-action in which the designer engages in a 'reflective conversation' with the design problem. He explains that in design activity, designers follow a process of path creation in which new understandings about the situation are created by making "moves" and evaluation or reflecting on said move and their significance on the path taken (Schön & Bennett, 1996). This means that designers engage on a process of discovering the design space and desirable path by building prototypes, testing them, and reflecting on what it means for the particular design problem (Cross, 2004; Schön, 1983; Schrage, 1996).

The process of Reflection-in-action process is based on the use of a *framing process.* The process as explained by Schön is cycle of four steps (Figure 2). First the designer *names* or stablishes the elements of the problem that will be addressed. Then a context or *frame* in which they will be addressed is created. Next the designer proposes experimental/temporary prototypes or *moves.* Finally, the designer tests and *reflects* on the results of said moves to either accept them as desirable moves or to propose new ones (Cross, 2004; Schön, 1983; Valkenburg & Dorst, 1998).

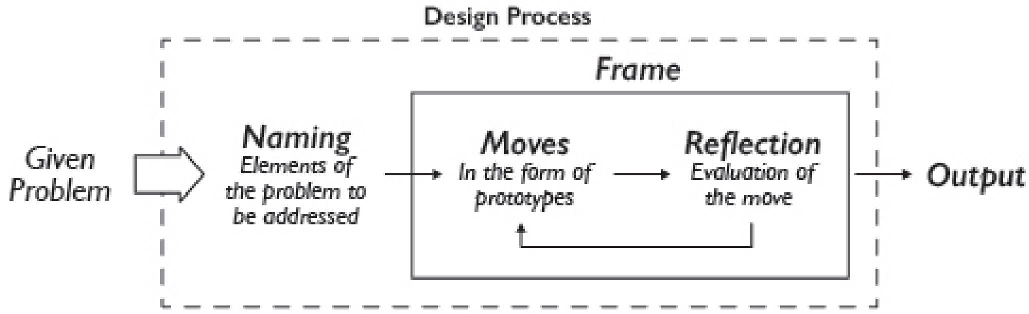


Figure 2. Reflection in action process cycle

When can see a clear connection of this process for prototype creation in the later stages of design (Figure 3). Here the problem has already been explored and the elements of the problem that will be addressed can be named, which allow the designer to propose a frame in which a series of possible moves can be proposed, evaluated, and reflect on their significance for a solution within this frame.

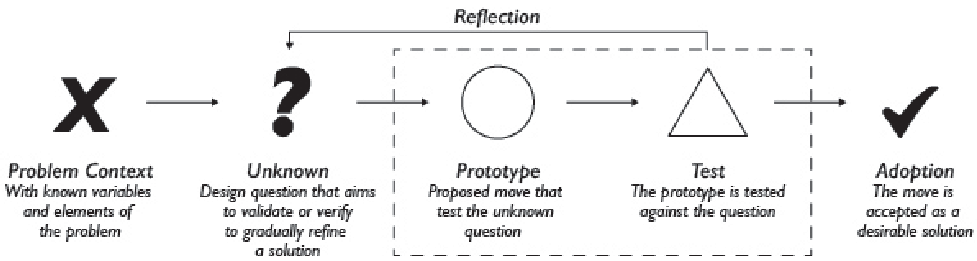


Figure 3. Solution focused reflection-in-action

Problem focused reflection-in-action

If we on the other hand look at the state of the different element on the earlier stages of design, we can observe that neither the problem has been sufficiently explored that will allow for the elements to be named nor a “permanent” frame can be created in which the designer can propose and evaluate moves. Yet, from our previous understanding of the design activity we can infer that instead of being in a state of paralysis over lack of problem definition, designer instead use prototypes to engage in active learning to provide definition to the problem (Figure 4). What changes is the element in which the designer reflects, and the question they ask of their prototypes, effectible using the temporary frame and temporary moves to reflect on the elements named. This task then places a lot of importance on the question the designer asks of its prototypes and the ability to not fixate on the artifact created but rather to focus the reflecting on problem definition.

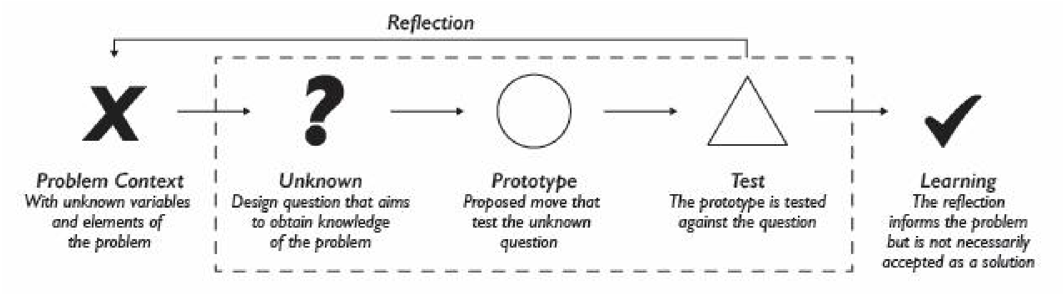


Figure 4. Problem focused reflection-in-action

Unintended Examples of Problem Exploration Prototypes

In this section we will use three examples taken from project of our Design Thinking course, and we will discuss them from the perspective of the problem focused reflection-in-action model previously discussed. The course itself has a structure of missions/milestones designed to guide the students through a design process that start with divergence and exploration of the problem are and later into a converging face to develop solution.

During the project the students are provided with a unique real-life project from a real industrial partner, design methodological content and a set of deliverables based on the state of the project. The missions in which the three examples where situated, belong to the early stages of the project.

In this stage students are asked to develop a deep understanding of the problem area and users within it, while at the same time create prototypes that answer non-evident design questions. The missions are very much intended for students to develop the ability ask non-evident design question based on their research and to create prototypes that prove those questions. While some students are able to use prototypes others struggle to use prototypes solely for problem exploration and become fixated on the artifact and the solution it offers to the problem. The three examples here presented, among others no in this paper, are of the groups of students who successfully used prototypes for problem exploration and allowed for a dissection and reflection of the actions performed that led to the model here presented.

Improving great looking eyes

Problem space: In this project the group of students was provided with a design brief from a multinational make-up company in which the company provided a very open challenge for exploration. The main prompt of the brief was how might we improved great looking eyes and what are problems that user experience when applying make-up.

Element of the problem: after a period of space exploration research, user interviews conducted, and testing of current solutions, the design team had discovered that there is a steep learning curve, high expertise level and time investment to obtain good results. This deterred many users from applying make-up on daily basis as they might have limited time in the morning before their daily routine began. Another finding that the team discovered was the perception of users that make-up application is a personal identity activity that is closely related to self-care and “me time”.

Question: These findings led the team to find a paradox of fast speed for results vs slow speed for enjoyment. From this the question that the team had about the problem and the user was: *Would user be willing to give up control of their daily make up routine to obtain better results?*

Artifact created: Based on this the team decided to construct an automated make-up machine (Figure 5a) with the premise of superfast application but no control over the results. You just put on the mask, pushed a button, and wait for the results. The machine was based on a wizard of oz prototype. The mask itself didn’t work at all and was just a modified mask (Figure 5b) to look like it could possibly be a real machine, and a real make-up artist equipped with an airbrush and hidden behind a door secretly performed the make-up application (Figure 6).

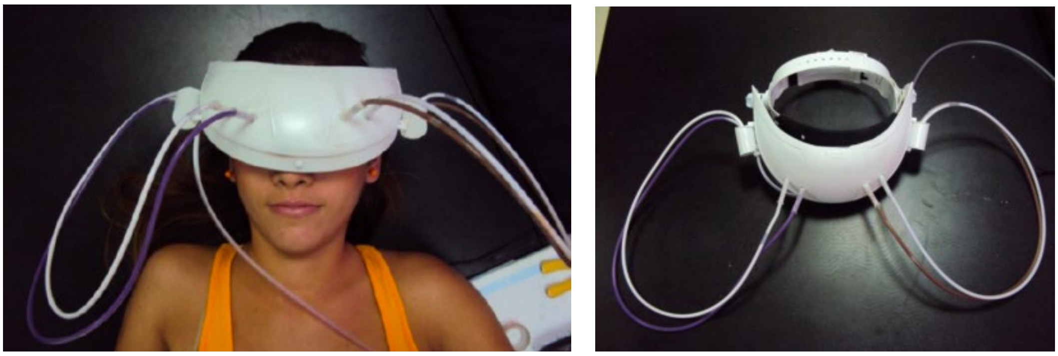


Figure 5a & 5b Automated make-up machine

Figure 6. Prototype testing

Problem reflection-in-action: In this case the machine was not technical feasibility. However, the team was not interested on the possibility of actually building the machine but rather to see the willingness of users to submit themselves to an automated process that offered great results but in which they had no control. In this case the design artifact was the make-up mask, but the prototype was the experience of automated make-up application that they use to better understand their users.

Contribution to problem-solving: In the end the design team didn't create a make-up application machine. The learning they extracted from that prototype gave them and insight in understanding that user would be willing to utilize simplified tools that limited their ability to customize results but that provided quick and effortless results with no learning curve and predictability in results.

Rescue in hard-to-reach terrain

Problem space: In this project the group of students was provided with a design brief that dealt with rescue operations from and industrial partner that collaborated with a research center for disasters. The main prompt of the brief was how might we extend the survival time of victims in emergency situation.

Element of the problem: Among the scenarios of research that the teams used was the Trängslet Dammen plane crash in the north of Sweden. This scenario exemplified a situation in which victims had to wait for a very long period of time before any help was provided due to the difficulties of the terrain in which it occurred. For the victim this meant that they had to endure very cold temperatures and lack of supplies while they waited for help to slowly arrive.

Question: The scenario presented, coupled with the teams' research on similar situations, led the student group to consider multiple physical prototypes of systems that contained all possible tools and equipment that victims could use while waiting for rescue services. The team explored the creation of a survival system and how to and where to place it that would be easily accessible and not interfere with cabin design or weight distribution on planes. However, the team discover that many similar kits or systems either already existed or could be easily assemble. This reflection led the team to a second question of accessibility to the tools and more specifically to *would passengers even think or remember to bring them in case the emergency was happening?*

Artifact created: Based on this question the team decided not to build the system of survival tools anymore but rather decide to test the issue of would it be useful in a case of emergency. For this the team decided to use a simulation of the tools represented by a pillow and constructed a simulation of a plane crash and to make it as stressful as possible (Figure 7). in the simulation, the aircraft crew, performed an A/B test in which they either gave detailed instructions to remember to bring the kit or just loosely mentioned it.

Figure 7. Simulation as prototype rather than the artifact

Problem reflection-in-action: In this case, once again the team was not after a technically feasible solution but rather, they wanted to better understand the behavior of people in stressful situations and how they would behave around feasible solutions. In this case the artifact was a representation of the kit in the form of a pillow, but the prototype was the testing platform of the simulation that allowed for testing of user behavior.

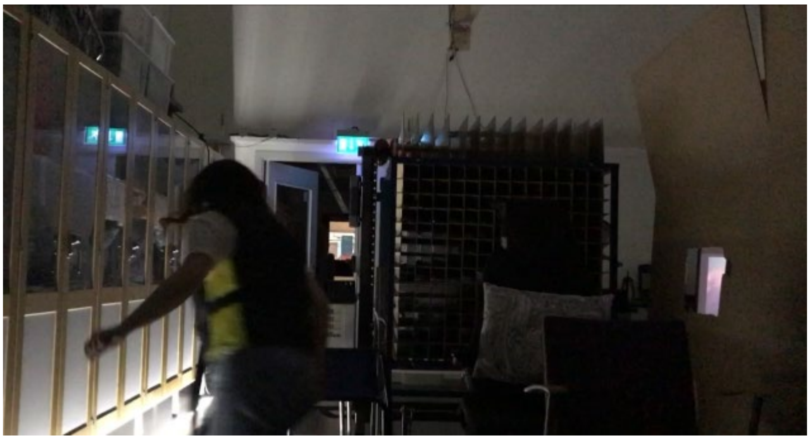


Figure 8. User in stress situation forgot the instructions given

Contribution to problem-solving: From the test conducted the team quickly discovered that in very stressful situation the users won't easily remember instructions no matter how elaborate (Figure 8). In the end the team reflected on the path taken once a new piece of information was found in a subsequent prototype that pointed to a very low incidence of plane related crashes combined with a very low survival rate after impact. Based on this discovery decided the team decided to change path to post disaster rescue in hard-to-reach areas but the learning that solution needs to be easy to use with minimal instruction and accessibility to user in very stressful situation was carried to final solution.

Medical imagery

Problem space: In this project the group of students was provided with a design brief that dealt medical images and the patient-doctor relation surrounding the use of said images.

Element of the problem: After the initial exploration period, where students conducted research and interviews, the group started to see a pattern of disconnection in between health professionals and the patients. They discover a twofold problem, first of prolonged waiting times in between the image been captured, and diagnosis been produced. second the problem of poor communication in the diagnosis segment of medical imaging as they are hard to read and require high expertise to do so. The problems are, of course, exacerbated on one hand by limited availability and time of medical professionals that can read, and interpret the images. And on the other hand, by impatience from patients that experience anxiety regarding their health issues.

Question: Based on these finding, the group of students started questioning several assumptions from the current state of the problem, like could it be possible to create medical images that are self-explanatory and don't immediately require a medical professional to evaluate them but can provide initial understanding to the patient. This path led the team to examine current medical images and how much can patients currently understand?

Artifact created: Based on this question the team decided to create several prototypes that aimed at helping patients to understand current images by either giving them a point of comparison or by providing an easier to read image. First, they presented a baseline to understand what healthy image looked like versus what the image of their condition looks like to stablish if they could understand their situation better (Figure 9a). And secondly the team provided patients with different sets of images in both 2D images (sliced view) and 3D images to stablish if seeing the bones or organs in their actual shape would facilitate understanding (Figure 9b).

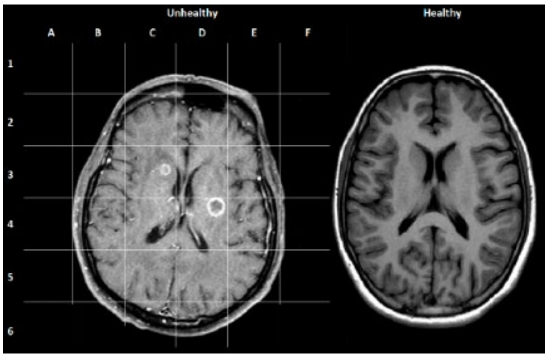


Figure 9a Comparison of healthy vs unhealthy image

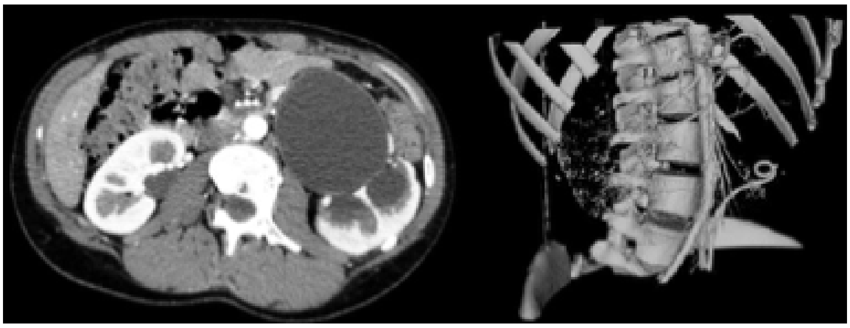


Figure 9b Comparison of 2D vs 3D representation

Problem reflection-in-action: In this case, once again the team was not after a technically feasible solution or digital system that could actually display the information to the patients. Rather, they explored what is they current level of understanding of images and how can it be enhanced by providing certain visual aids. The artifacts use where simple modified images either printed or in a PowerPoint deck which they used to test with the users (Figure 10).

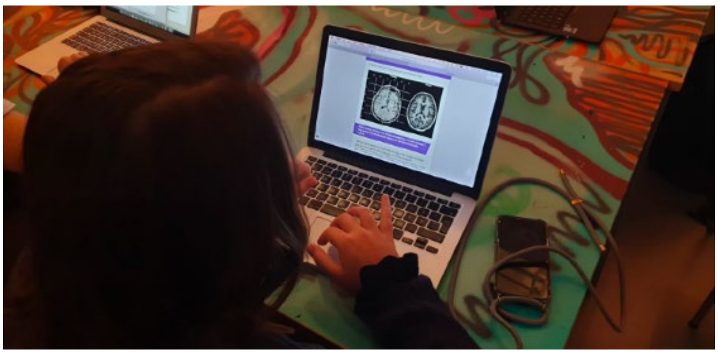


Figure 10. Prototype testing

Contribution to problem-solving: In the case of this team, the reflection and learning from this early prototype was rather a big “failure” from the perspective of the artifact, but a great success in terms of defining their problem area. The students discovered that patients had a bigger tendency to overreact, misinterpret and misidentify basic elements from the images. From the medical community they also discovered that not providing a full load of information on the patient is part of the diagnosis as to not overwhelm and further produce anxiety. For the long-term project this prototype served to dissuade them from the path of self-diagnosis but pointed at and interesting revelation of visualization of same object in multiple modes in a common platform to simplify communication between image technicians who communicate 2D and doctors who communicate in 3D.

Summary/Conclusions

In design education, a range of models and prototypes get generated by students. A degree show, with appearance models (Pei et al., 2011) on pedestals, is experienced by many students as the celebratory culmination of their many years of study. But as Pei (ibid) made clear so nicely in his taxonomy of design representations, different types of models and prototypes each have their function, to either explore, validate, or communicate aspects of our design.

Academically trained designers may be expected –even though current practice might be different– to explicitly articulate and argue for the type of design representation they will use, as well as at which fidelity they will create it.

Design education should train students both at the skills to create different types of design representations, as well as in strategically employing them. Current educational practice may well fall short on this.

Here however, we raise yet another question: if we were to have programs properly training students on the use of different models and prototypes, how would such training further evolve once we challenge students to employ prototypes purely for the exploration of their problem? Basically, all the sketches, drawings, models, and prototypes included in Pei’s taxonomy are solution-oriented.

The easy first step to take is to challenge students to start creating prototypes even earlier and use them in interactions with participants from their problem area. Asking at each coaching session, as we do in our weekly feedback sessions on the design thinking projects, what they have built and what they have learnt from their prototypes helps.

It also requires a mindset from teachers to except that they have no clue where a project will end up. Experienced design teachers will be able to see potential (and will have to bite their tongue to not point it out to students).

Proper briefing is of paramount importance, for projects where you want students to explore their problem space through prototyping. Briefs should be sufficiently open, or students need to be actively steered towards challenging the brief if it is more closed.

References

Archer, B. (1979). Design as a discipline. Design Studies, 1(1), 17–20. https://doi.org/10.1016/0142-694X(79)90023-1

BenMahmoud-Jouini, S., & Midler, C. (2020). Unpacking the notion of prototype archetypes in the early phase of an innovation process. Creativity and Innovation Management, 29(1), 49–71. https://doi.org/10.1111/caim.12358

Buchanan, R. (1992). Wicked Problems in Design Thinking Author (s): Richard Buchanan Published by : The MIT Press. Design Issues, 8(2), 5–21.

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2017). Design prototyping methods: State of the art in strategies, techniques, and guidelines. Design Science, 3. https://doi.org/10.1017/dsj.2017.10

Cross, N. (1982). Designerly ways of knowing. Design Studies, 3(4), 221–227. https://doi.org/10.1016/0142-694X(82)90040-0

Cross, N. (2004). Expertise in design: an overview. Design Studies, 25(5), 427–441.

Domingo, L., Moore, D., Sirkin, D., Toye, G., Leifer, L., & Cutkosky, M. (2020). Strategic Prototyping to Learn in Stanford University's Me310 Design Innovation Course. Proceedings Of the Design Society: Design Conference. https://doi.org/10.1017/dsd.2020.176

Gero, J. S. (1990). Design prototypes: a knowledge representation schema for design. AI Magazine, 11(4), 26.

Goel, V., & Pirolli, P. (1992). The structure of design problem spaces. Cognitive Science, 16(3), 395–429. https://doi.org/10.1016/0364-0213(92)90038-V

Houde, S., & Hill, C. (1997). What do Prototypes Prototype? In Handbook of Human-Computer Interaction (pp. 367–381).

Lande, M., & Leifer, L. (2009). Prototyping to learn: Characterizing engineering students' prototyping activities and prototypes. DS 58-1: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 1, Design Processes, Palo Alto, CA, USA, 24.-27.08. 2009.

Lawson, B. (2006). How designers think. In How Designers Think. https://doi.org/10.4324/9780080454979

Menold, J., Jablokow, K., & Simpson, T. (2017). Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. Design Studies, 50, 70–112.

Pei, E., Campbell, I., & Evans, M. (2011). A taxonomic classification of visual design representations used by industrial designers and engineering designers. The Design Journal, 14(1), 64–91.

Rothenberg, J. (1991). Prototyping as modeling: what is being modeled? In Dynamic Modelling of Information Systems (pp. 335–359). Elsevier.

Rudd, J., Stern, K., & Isensee, S. (1996). Low vs. high-fidelity prototyping debate. Interactions, 3(1), 76–85.

Ruiz, J. (2020). The Problem of Formulating Design Problems: A Typology of Design Briefs (Vol. 1895). Linköping University Electronic Press.

Ruiz, J. F., & Wever, R. (2022). The Best Of Times, The Worst Of Times; Student Design Team Formation. DS 117: Proceedings of the 24th International Conference on Engineering and Product Design Education (E&PDE 2022), London South Bank University in London, UK. 8th-9th September 2022.

Schön, D. (1983). The reflective practitioner: How professionals think in action. In The Reflective Practitioner: How Professionals Think in Action. https://doi.org/10.4324/9781315237473

Schön, D., & Bennett, J. (1996). Reflective conversation with materials. In Bringing design to software (pp. 171–189).

Schrage, M. (1996). Cultures of prototyping. Bringing Design to Software, 4(1), 1–11.

Simon, H. A. (1973). The structure of ill structured problems. Artificial Intelligence, 4(3–4), 181–201. https://doi.org/10.1016/0004-3702(73)90011-8

Smy, V., Cahillane, M., & MacLean, P. (2016). Sensemaking and metacognitive prompting in ill-structured problems. International Journal of Information and Learning Technology, 33(3), 186–199. https://doi.org/10.1108/IJILT-10-2015-0027

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2008). Product design and development (Vol. 4). McGraw-Hill higher education Boston.

Valkenburg, R., & Dorst, K. (1998). The reflective practice of design teams. Design Studies, 19(3), 249–271. https://doi.org/10.1016/s0142-694x(98)00011-8

Virzi, R. A. (1989). What can you learn from a low-fidelity prototype? Proceedings of the Human Factors Society Annual Meeting, 33(4), 224–228.

Virzi, R. A., Sokolov, J. L., & Karis, D. (1996). Usability problem identification using both low-and high-fidelity prototypes. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 236–243.

Voss, J. F. (2005). Toulmin's model and the solving of ill-structured problems. Argumentation, 19(3), 321–329. https://doi.org/10.1007/s10503-005-4419-6

Juan Ruiz

Juan Ruiz is a researcher and teacher in design engineering and product development at the Division of Product Realisation at Linköping University, Sweden. He has both practical and teaching experience in user-centered design, design methods, and Design Thinking methodology as tools for complex problem solving, design innovation, and product development, focusing on areas of problem formulation, problem exploration and research, prototyping, and technology-driven market creation, among others. His research focuses on design problem-solving, in which he has conducted research on the topics of problem formulation and prototyping in the early stage of the design process and the consequences that both of these aspects present to problem solving. He has also conducted research on design engineering education that focuses on team formation and student collaboration within design challenge-based education.

Dr Renee Wever

Dr Renee Wever is a Professor at the Linköping University, Department of Management and Engineering, Division of Product Realisation. He holds a MSc and PhD in Industrial Design Engineering from Delft University of Technology in the Netherlands. His research interests are design research, circular economy, packaging design, sustainable behaviour, and sustainability in the front end of innovation. He has (co)authored some 20 journal articles on these topics as well as numerous conference papers. He has supervised multiple doctoral students who were working on design processes, tools, and methods, including prototyping. Since 2013, he has also served as editor for the Journal of Design Research.

Process as prototype: exploring complex knowledge exchange in the production of low-cost buoyancy aids in Zanzibar through the participatory design of a 'workflow system'

Emma Shercliff, Arts University Bournemouth, UK
Lucy Devall, Buro Happold, UK
Franziska Conrad, University of Southampton, UK

Abstract

This paper reports on an investigation into the role of experiential knowledge in growing capacity for producing low-cost buoyancy aids with soft goods manufacturers – tailors – in Zanzibar, set within complex knowledge exchange collaborations under academic-industry partnerships. In this study, the makers' practice of tailoring and their local environment knowledge had a formative role in designing a prototype 'workflow system' for local, small-batch production of low-cost rescue throwlines as part of a wider community-led water safety programme.

The study builds on a previous phase of the research that identified limitations with a human-centred design (HCD) approach to the creation of opensource instruction manuals for low volume production of rescue throwlines. We propose that the previously incumbent HCD approach through its problem-solving procedures obscured the importance of the local makers' participation in the *problematisation* of the manufacturing process. By foregrounding the local makers' knowledge of the whole manufacturing process, from sourcing materials in the market to making and testing the products, this study aimed to investigate how the local makers would devise and develop their own methodological approach to making the rescue throwline, examine what the findings would suggest for the design of the throwline, and explore how this knowledge might be exchanged with other collaborators in the project. A further and longer-term aim is to support the development and impact of local capacity building in end-to-end drowning prevention management by demonstrating the importance of experiential knowledge in existing local communities of makers.

A participatory making approach informed by design thinking underpinned the design of the study. An experimental participant-led approach to the generation of data draws attention to the different positions and types of knowledge negotiated. The study elucidates some of the barriers for exchanging this critical experiential knowledge with collaborators and exposes challenges for creating new social infrastructure within the community concerning drowning prevention. It concludes that managing complex knowledge exchange in prototyping in the Zanzibar context requires an iterative methodological approach to the co-construction of knowledge centred around the experiential knowledge and skills of the users of the 'workflow system'.

Experiential knowledge; participatory design and making; workflow system; drowning prevention; complex knowledge exchange.

The United Republic of Tanzania (URT), which includes Zanzibar, is one of the countries whose population is most vulnerable to death by drowning (WHO, 2014; Sarrassat et al, 2019). As a result of wider advocacy work by the Royal National Lifeboat Institution (RNLI) and others, in April 2021 the United Nations (UN) passed a Resolution setting out urgent action for drowning prevention across all countries and UN agencies[1] – the first in its 75-year history. One of the key factors leading to this intervention has been the inability of local communities and small organisations in low-resourced countries, like Tanzania, to sustain the production and upkeep costs of specialist manufactured ISO standard drowning prevention devices, such as the rescue throwline in Figure 1. In response, the RNLI has been working with global partner organisations to research and develop community-led water safety capacity[2], which includes developing capability for producing life-saving buoyancy aids such as low-cost rescue throwlines.

Figure 1: ISO standard rescue throwline designed and manufactured by Eval in Greece (2020). Object number: AIBDC: 009367. Photo: MoDip, Arts University Bournemouth.

Since 2019, the Arts University Bournemouth has been consulting with the RNLI to deliver manufacturing guidance and tools that can be managed in-country by communities and local NGOs. One of the core activities has been to grow capacity for producing low-cost rescue throwlines that adhere to RNLI safety-critical standards, thereby omitting the need for costly intermediary supply chain actors and increasing the likelihood of community involvement. In doing so, this project works towards a theory of change such that as new markets in drowning prevention capacity open up, so too do possibilities for entrepreneurship and sustainable socioeconomic growth. Out of this, the Arts University Bournemouth established

[1] https://rnli.org/news-and-media/2021/april/29/un-adopts-historic-first-resolution-on-global-drowning-prevention (Accessed 16th January 2023)
[2] https://rnli.org/what-we-do/international (Accessed 16th January 2023)

a partnership with Pamoja Zanzibar (Pamoja), specifically Pamoja's tailoring school[3] based in Kisauni, Zanzibar, and conducted several creative design workshops in-country (Conrad & Devall, 2020).

This paper focuses on a period of activity conducted in 2021 between the Arts University Bournemouth and Pamoja. It discusses aspects of this process of growing capacity focussing on the complexity of knowledge exchange across disciplines, institutions and cultures. It concerns the role of participatory design and maker knowledge in grassroots innovation, and in particular the intangible knots of experiential knowledge that we discovered to be crucial in refining the prototype of an appropriate, context-specific workflow system for producing low-cost rescue throwlines. The activities presented here took place in Zanzibar at Pamoja, and the research team worked remotely from the UK due to prohibitive international travel restrictions as a result of the Covid-19 pandemic.

The background to the problem

The complexity involved in undertaking collaborative and interdisciplinary projects, particularly where creative design and making practices are concerned, presents opportunities for design research (Bowen et al, 2016). In this instance, the RNLI and its water safety partners initially applied a human-centred design (HCD) approach to the development and testing of a new-to-the-market product, the rescue throwline, drawing together expertise in water safety, product design and user-centred design. The HCD approach primarily involves users and stakeholders in the *problem-solving* design process, rather than *problematisation* (Vines et al, 2013), which is an important distinction to point out, especially in this instance where the success of the drowning prevention programme depends on community uptake and ownership. Problematisation here is approached as a collaborative process of problem formulation, where the "nature of problems" is explored and refined through creative practice (*ibid* 2013, p.192). In such settings, the frame within which a design thinking approach is applied can create the constraints to enable (or disable) instrumental value in the process (Dorst, 2011). This value is intrinsically tied to the experiential knowledge of all stakeholders. Furthermore, it can lead to enhanced uptake when the knowledge about the product's purpose and its features is expected to transfer across complex disciplinary, socio-economic, cultural and linguistic boundaries without resistance, misunderstanding and/or rejection.

Whilst we acknowledge that the research team has expertise in design, making and innovation developed in a largely Euro-western context, and "brings to bear … a cultural orientation, a set of values, a different conceptualization of such things as time, space and subjectivity, different and competing theories of knowledge, highly specialized forms of language and structures of power" (Tuhiwai Smith 2021, p.49), we understand the importance of expanding design research methods towards a more inclusive approach, particularly in the framing of the problematisation process. In Zanzibar, where manufacturing capacity is very small scale and makers are likely to be closely involved in the whole

---

[3] Pamoja Zanzibar is an NGO, based in Kisauni outside Zanzibar City, that offers vocational training programmes and qualifications in car mechanics and tailoring as well as water treatment facilities: https://www.pamojazanzibar.org/index.php/en/ (accessed 27th January 2023).

process of product development and use, we determined that the HCD design thinking approach employed previously, obscured the importance of *participation* as a way of designing for and *with* people. The local community of makers, although they had not been directly involved in the problem-solving process of designing the rescue throwline, were important components within the complex knowledge exchange process. Reframing the problematisation process, with their participation, around the context of manufacturing capacity identified a new set of problems and brought a new perspective to the bigger picture of capacity building. By bringing in a creative participatory design approach to capacity building that includes the experiential knowledge of local communities of makers in developing prototypes of supply, manufacturing and testing processes, we propose that a broader group of stakeholders can be engaged in the ownership of the drowning prevention management process.

The research presented here builds on the challenges of the product prototyping observed in previous iterations by Conrad and Devall (2020), which explored the ability of Pamoja's tailoring community to adopt opensource instruction manuals produced as a result of the RNLI's earlier HCD research on the design, development and testing of the new-to-the-market throwline. Conrad and Devall (*ibid*) found that the opensource instruction manuals had been designed for makers familiar with industrial scale manufacturing systems and were not adapted appropriately to the Zanzibar context. Furthermore, these manuals failed to reflect the role of experiential knowledge in successfully making a throwline to the RNLI safety critical standards.

Project aims and objectives

Given the importance of involving local makers in problematising the manufacturing process in order to negotiate the complex collaboration necessary for low-cost throwline development and local community management of drowning prevention strategies in low-resource settings, our intentions were to:

- investigate how the makers (Pamoja tailors) would devise and develop their own methodological approach to making the rescue throwline.
- examine what the findings would suggest for the design of the throwline.
- explore how this knowledge might be exchanged with other collaborators in the project such as the RNLI.

Characteristics of 'designerly thinking' have been applied using the role of making as inquiry (Johansson-Skoldberg, Woodilla & Cetinkaya, 2013; Cross, 2007). In this research, the role of making as inquiry extends to include participatory making, which allows for a more inclusive approach to community participation, and importantly provokes questions concerning skills, ways of working and positions of knowledge. For instance, local environmental knowledge has been exchanged through engagement in activities with participants (Berg, 2008) that centres their expert knowledge developed in the Zanzibar context.

As mentioned above, the buoyancy aid in focus for this study is a low-cost 18m long rescue throwline designed and developed in 2019 by the RNLI International team. An instruction manual for making the rescue throwline, initially developed by the RNLI and revised by the Arts University Bournemouth research team (Conrad & Devall, 2020), is available as an opensource download via the RNLI website[4] (Figure 2). The design and its safety-critical features as presented in this document are referred to as the template for how the product should look and function.

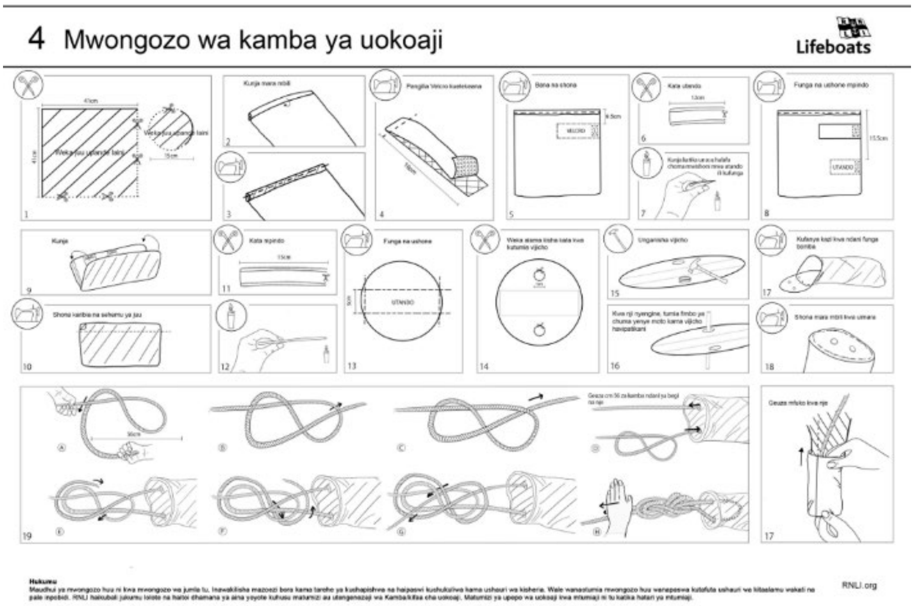


Figure 2: An example page from the low-cost 'Rescue Throwline Manual' in Swahili, an opensource download tool available from the RNLI website.

The rescue throwline is made from a bright orange nylon fabric bag with black webbing handles, stainless steel eyelets and a twisted polyethylene rope (see Figure 3). All materials need to be available to buy locally. Local makers with capabilities in small-scale soft goods making[5] and a situated knowledge of supply chain capacity within the Zanzibar region were identified as participants for this study: the Pamoja tailors.

[4] https://rnli.org/what-we-do/international/international-resources - 'Rescue Throwline Manual' (Accessed 16th January 2023)

[5] Known as 'tailors' in Zanzibar, and hence referred to as tailors here.

Figure 3: The rescue throwline product prototype, designed by the RNLI International team and produced by Pamoja tailors, Zanzibar (2019). Object number: AIBDC: 008485. MoDip, Arts University Bournemouth.

Methods

Returning to the project aims and taking into account the importance of involving local makers in problematising the manufacturing process in order to better understand how to move towards a participant designed 'workflow system', we set out to learn from the tailors how they set about making the throwlines from sourcing the necessary materials, through to making and testing the products. For this, the study used a combination of methods. Over a period of two months in 2021, meetings and discussions were held with the Pamoja tailors on Skype interspersed with workshop activities undertaken by the tailors on location at Pamoja's tailoring school. We devised specific tasks for the workshop activities to interrogate the tailors' process and question prompts to guide documentation. In asking the tailors to describe their processes more explicitly than they might otherwise, the objective was to elicit context relevant detail about their approach to making the rescue throwlines. This in turn informed the participatory approach to designing the 'workflow system'. These activities were organised around six stages:

1. Mapping the tailors' capabilities and Pamoja's capacity for manufacturing the rescue throwlines.
2. Gathering materials needed, e.g. sourcing fabric, rope and notions from the market.
3. Preparing materials for production, e.g. cutting out requisite amounts of fabric and rope.
4. Making and testing the rescue throwlines, including further problematisation of

making techniques.
(Two iterations of stages 3 and 4 enabled refinement and consolidation of the production process.)

5. Trialling ways of communicating the process for exchanging the experiential knowledge of resourcing, manufacturing and testing the rescue throwlines.
6. Devising the guidelines for the 'workflow system'.

A research assistant/translator was employed on location to facilitate discussion between the English-speaking research team and the Swahili-speaking tailors. The Skype meetings held at the Pamoja tailoring school were recorded and documentation of the tasks/workshop activities including photographs, short video clips and voice memos were sent back to the research team via WhatsApp by the translator. The advantages of using WhatsApp were a) it is an affordable instant messaging service that required no additional costs or equipment from participants and b) it facilitates the collection of 'real-time' data over both time and place (Manji et al, 2021). Methodologically speaking, this approach to participant-led data generation was new for the research team and we welcomed this as a way to build trust and adjust the balance of power between researchers and participants (Kara, 2018). Visual and text-based analysis of the data was shared with participants using an online whiteboard tool (Miro) throughout the length of the study.

The project: understanding the makers' process and creating the prototype workflow system

Returning to the project aims and taking into account the importance of involving local makers in problematising the manufacturing process in order to better understand how to move towards a participant designed workflow system, we first set out to observe how the tailors make the throwlines from sourcing the necessary materials, through to making and testing the products. We devised specific tasks to interrogate their process and question prompts to guide documentation.

Some of the tailors at Pamoja had already been involved in earlier stages of the research in 2019, including the head tailor, Josephina, and her deputy, Mwanahamis. In order to avoid overlooking any essential information that might have become absorbed intuitively into the embodied knowledge of making held by Josephina and Mwanahamis, we stipulated that they work with at least one tailor with no prior experience of making the throwline to be able to report back to us on their learning. We worked with five tailors for this study: the head tailor, her deputy, two trainee teachers, Almish and Zainab, who had been involved in making throwlines previously, and one tailor with no prior experience of making the throwline, Mwajuma.

An initial mapping exercise established the tailors' making capabilities, their role in the Pamoja organisation, their skills, access to equipment and other claims on their time. This enabled us to understand the scope of possibilities and the limitations. All participating tailors held a tailoring qualification and worked independently, either on individual commissions or producing soft goods for the tourist economy, as well as at the tailoring school. All had access to sewing machines. All held other jobs in addition to their tailoring such as farming and animal husbandry, cooking and domestic duties.

This was followed by a trip to the market in Stone Town, led by Josephina and Mwanahamis, to source and buy the materials needed to make two batches of ten throwlines, overseen by Josephina. The first batch was made to problematise the process, identify and document any challenges; the second batch was made to confirm the workflow system as a proof of concept.

The next stages of the project involved exploring ways to formulate and communicate the knowledge gained. This was achieved through two 'chemsha bongo' (brainstorming) sessions, led by the research assistant on site, that explored the best ways to show and explain how to make the throwlines respecting the critical safety standards required (see Figure 4). This involved a combination of description, drawings, making samples of certain components and additional revisions to the original manuals.

Figure 4: 'Chemsha bongo' brainstorming session at Pamoja: exploring ways to formulate and communicate the tailors' knowledge.

A final stage resulted in the drafting of guidelines embracing the whole workflow system that can serve to pass on the knowledge of how to make the throwlines to other tailors. These guidelines, in Swahili, with added illustrations and short video clips, make reference to explicit procedural knowledge (Niederrer, 2007), such as the correct measurements required and how to secure the holes for the rope to pass through, as well as an implied experiential knowledge (*ibid*) specific to the tailors' context in Zanzibar, such as 'window shopping' for sourcing materials and pulling on the rope to test the security of the knot.

The role of experiential knowledge in developing the 'workflow system' prototype

Conrad and Devall (2020) had already shown that the opensource instruction manuals only partially succeeded in exchanging knowledge of the critical safety standards embodied in the RNLI designed throwline. The knowledge exchange 'system' of instruction manuals did not completely fulfil its role. Smith et al (2017), argue for "increasing creative input from workers" (p.39) in relation to the introduction of new technologies into production processes, stating that “systems designed without thought for user skills resulted in serious failures, as well as resistance” (Smith et al. 2017, p.39). The Pamoja tailors, users of the system in question, found that the manuals did not reflect essential information specific to how they apply their skills in their particular context. As a result, the manuals were not used by the tailors as intended. They preferred to refer to the product prototype instead, bypassing sections of the instruction manuals, and drawing directly on their own experiential knowledge of making processes accumulated with the basic tools they are used to using (e.g. second-hand domestic sewing machines, scissors, dress-making tape measures, chalks for tracing the fabric pieces) and the spaces they are familiar with.

Soft-goods manufacturing – tailoring – in the Zanzibar context is small-scale and largely part of the informal economy (Bonnet et al, 2018)[6]. As an indication of the manufacturing capacity, Pamoja, an established organisation, could manage the production of batches up to a maximum of 100 throwlines, but would cut out and make them one at a time. Individual tailors are more likely to work from their homes with considerably less capacity. Tailoring in Zanzibar is a grassroots livelihood without supply chain infrastructure and streamlined manufacturing. The tailor making the buoyancy aid is also sourcing and transporting the materials, preparing space for the production process, sewing and testing the product; they are involved in the whole manufacturing process.

We realised the knowledge necessary to be able to reproduce these rescue throwlines and pass the knowledge on to others cannot be wholly and reliably contained in an opensource instruction manual; it is distributed across the whole process. Instructions for making the products needed to extend to guidelines for the whole process. The prototype we were therefore developing with the tailors was a context specific ‘workflow system’ - a design process that supersedes the design of the physical product. The tailors’ experiential knowledge – the knowledge accrued from their experience of sourcing supplies in the market, calculating quantities and preparing for production with little space, basic tools and using second-hand sewing machines – was essential for its development. A participatory design approach (Vines et al, 2013; Halskov & Hansen, 2015) was necessary to facilitate the exchange of this knowledge across the disciplinary, socioeconomic, cultural and institutional boundaries. As with a product prototype, there were iterations of this process in order to better understand how it worked for the tailors and identify points of difficulty or misunderstanding that required clarity in order to ‘write down’ the workflow system.

What follows is a discussion of three key instances that demonstrate the crucial role played by experiential knowledge in the design of this prototype workflow system:

- Procuring materials
- Using appropriate technologies
- Testing safety critical standards

Procuring materials

Developing the workflow system took into account the whole making process and highlighted the place occupied in this process by the procurement of materials. As mentioned above, the tailor

[6] Women are more likely than men to be occupied in sectors of the informal and semi-formal economy in Tanzania (such as tailoring) by 2.5 to 5 percentage points.

making the throwline is also sourcing and transporting the necessary materials. All materials for making the throwline are sourced at the central market in Stone Town from chandlery stalls, haberdashery stalls and other related suppliers such as shoe manufacturers. Knowledge of where to find the necessary materials is gained by ‘window shopping’, whereby the tailors, in a small group of three, visit the market together to seek out the best and cheapest suppliers of the materials needed. There are a limited number of suppliers in the market and stock needs to be assured. Familiarisation of the materials used, prices and where to find them is achieved by regular visits to the market. Josephina, the head tailor, recommends tailors go ‘window shopping’ before buying what is needed:

> Josephina normally does ‘window shopping’ first to scope out the materials and components for prices and location but the prices fluctuate so you still need to keep in mind what might be the case for different prices on the day.[7]

‘Window shopping’ is then usually followed up with a second trip to buy the materials identified. However, for this study, she felt it was important the tailors have the whole experience of going to the market and walking around to find *and* buy what they need, emphasizing the need to gain experience of the searching, calculating and negotiating required, as well as knowing what to look for:

> Josephina decided to take the whole team to the market and do the scoping and purchasing together (rather than in two different trips) so the team can get a feel of how much you’d need to decide when selecting supplies.

For the purposes of this study, Josephina wrote a shopping list to calculate how much/many of each component was needed for making ten throwlines. Normally, this information would be memorised. Exact quantities are bought for the number of throwlines to be made. Where quantities are packaged up approximately, prior knowledge of what is sufficient for the task is essential. For example, the polyethylene rope is sold in bundles of approximate lengths of 17-19m and it makes sense to use a whole bundle per throwline rather than waste small lengths to achieve precision to the nearest millimetre.

[7] Quotes are taken from voice memos translated from Swahili to English by the translator.

Figure 5: Sourcing supplies: tailors shopping in Stone Town central market for materials to make the throwlines.

The experience of sourcing materials also includes journeying to and from the market. Tailors may take the ‘dala-dala’ (public transport) or be driven to the market in the car owned by Pamoja. In this instance it was more efficient to use the Pamoja car to transport bulky bundles of rope and fabric. In either case, the amount of fabric and rope bought is limited by what can be carried on foot.

Figure 6: Transporting supplies: Mwanahamis and Zainab carry the bundles of rope from the market to their transport.

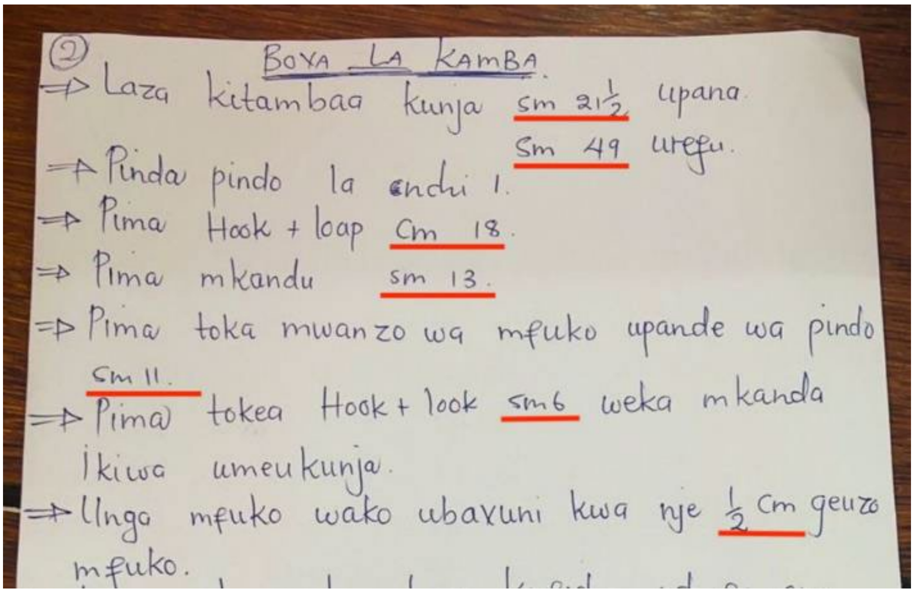
The knowledge required to successfully procure materials for making the throwlines in the Zanzibar context is not theorized and automated by a system operated by other interlocutors distanced from the makers (Smith et al, 2017; Tuhiwai Smith, 2021). Knowledge of how and where to source materials can only be fully understood by the tailors if they go to the market in person, literally pacing out their knowledge by walking round the market and talking to suppliers in person, familiarizing their whole bodies with the task. This knowledge is experienced physically and is not usually written down but held in memory. The experiential knowledge concerning the procurement of materials is also described by the limitations of the body; knowing how much can be bought in one trip is limited by how much material can be carried on foot. In turn, this influences how many throwlines can be made at any one time and therefore, has implications for building capacity and socioeconomic growth. Understanding this knowledge position, and its limitations (as seen through our Euro-western lens) has been crucial in the development of the workflow system but does present challenges for the exchange of knowledge with other stakeholders.

Using appropriate technologies

Use of the term ‘appropriate technologies’ here is informed by principles aligned to the Appropriate Technology (AT) movement: “a more situated, environmentally concerned and socially just set of design and operational principles for diverse technology choices by involving local communities” (Smith et al, 2017, citing Kaplinsky, 1990), and their experiential knowledge of their environment (Berg, 2008).

Firstly, the use of millimetres in the measurements cited in the original opensource instruction manual should be highlighted. This is standard practice used in prototyping and knowledge exchange by designers and engineers in a high-volume manufacturing context. The assumption that it would be so in the Zanzibar soft goods manufacturing context exposes the different knowledge positions held by the different partners in the project, and indeed the imbalance of power. In practice, the tailors, without access to precision tools, default to their habitual use of centimetres measured using tape measures (see Figure 7) and this was reflected in the amended instructions developed during the ‘chemsha bongo’ sessions as seen in Figure 8.

Figure 7: Preparing for production: measuring out fabric in centimetres using a tape measure.



(2) BOYA LA KAMBA
⇒ Laza kitambaa kunja sm 21½ upana
sm 49 urefu.
⇒ Pinda pindo la inchi 1.
⇒ Pima Hook + loap Cm 18.
⇒ Pima mkandu sm 13.
⇒ Pima toka mwanzo wa mfuko upande wa pindo
sm 11.
⇒ Pima tokea Hook + look sm6 weka mkanda
ikiwa umeukunja.
⇒ Ungo mfuko wako ubavuni kwa nje ½ cm geuza
mfuko.

Figure 8: Working in centimetres: instructions for making the throwline indicating measurements in centimetres.

Second, as trust built between the research team and the Pamoja tailors, particularly through the latter stages of the project and the 'chemsha bongo' sessions, they initiated alterations to the original design of the throwline. Stainless steel eyelets, as specified in the instruction manuals, as used in Figure 9, were abandoned in favour of a self-faced hole in the fabric (see Figure 10).

Figure 9: Inserting stainless steel eyelets in the base of the throwline to reinforce the holes as stipulated by the original instruction manual and in the original prototype.

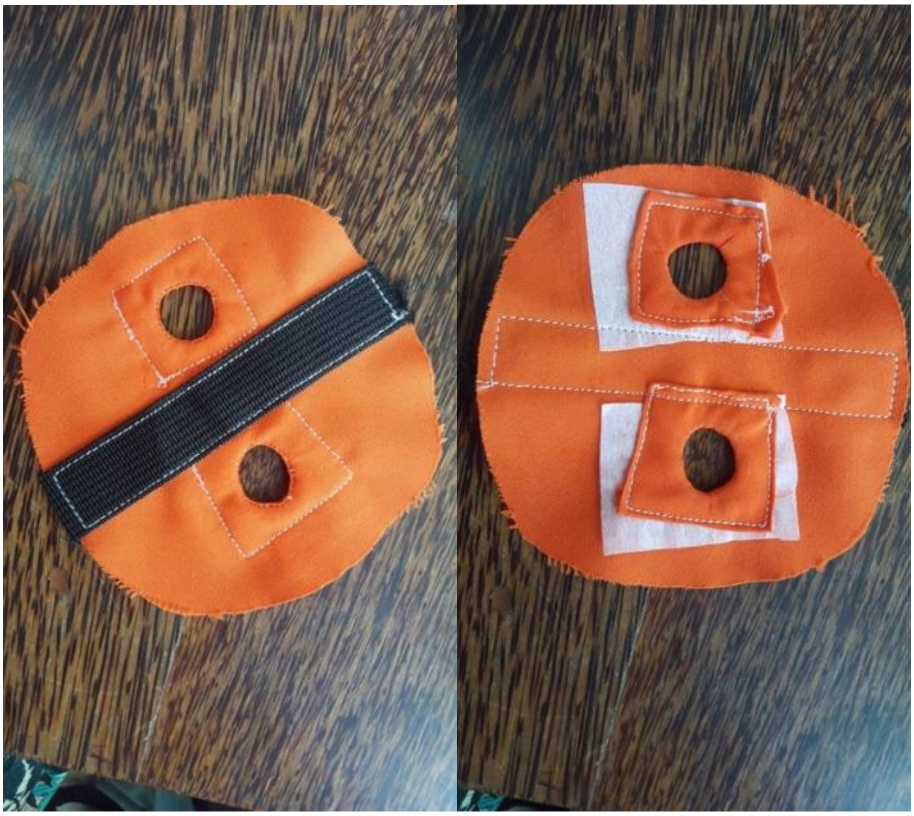


Figure 10: The tailors' modified design: self-faced reinforced holes.

These alterations were prompted by their knowledge of their local environment. The sea water around Zanzibar has a high saline content, which results in the rapid rusting of metal components, thereby shortening the product's useful life and/or risking product failure. In addition, the Stone Town market stalls have an unreliable supply of correctly sized eyelets. A more reliable and dependable method was devised. The tailors' experiential knowledge facilitates this initiative and we see them becoming active agents of innovation making their own appropriation (Smith et al, 2017 p.11) of the throwline. Problematizing the process (Vine et al, 2013) in the initial stages of this study with the tailors and creating opportunity for them to reflect on their knowledge through the 'chemsha bongo' sessions, resulted in them leading the problem-solving stage of the project.

Testing safety critical standards

It is important to note that the rescue throwline is part of a series of products and activities within the Zanzibar-based RNLI water safety programme. On its own, it cannot replace other devices relied upon to save lives, but it can be used as part of growing capacity for drowning prevention. To this end, it is crucial that the throwline meets the RNLI safety standards.

The throwline is intended to be thrown from a place of safety on dry land to a person in difficulty in coastal waters. The end of the rope is held by the person on the shoreline and the bag containing the length of rope is thrown to the person in difficulty in the water. A handle at the base of the bag allows the person in the water to hold onto the bag and be pulled to safety. The handle is created by knotting a loop securely into the length of rope. It is imperative this knot holds fast; if it is not tied securely and slips undone, the person in difficulty could become detached from the bag and the throwline fails.

Tying a knot is challenging to represent in instruction manuals, whether as an image or in words, or a combination of both. Knowing how to tie a knot relies on tying the knot in real time, sensing the journeys of the rope over and under and through the various loops created by fingers and hands. Knowing if the knot is secure depends on feeling the rope pulled under tension and simultaneously watching for any signs of movement that will indicate slippage. Figure 11 shows the tailors testing the security of the knot.

Figure 11: Two people pull on the rope, holding the handle to test the security of the knot.

Perhaps even more than other stages of the throwline production, tying the knot requires an experienced makers' "constant interplay between tacit knowledge and self-conscious awareness, the tacit knowledge serving as an anchor, the explicit awareness serving as critique and corrective" (Sennett, 2008 p.50). However, the experiential knowledge of tying the knot correctly and securely evades description in two-dimensional illustrations. Instead, the tailors made short video clips of the knot-tying process, which helped by allowing them to view the process objectively and identify critical gaps in the manual illustrations. Although to some extent still unresolved, this resulted in an improved and more detailed visual explanation. Figures 12 and 13 show the gaps in the original instructions completed by new drawings made by the tailors.

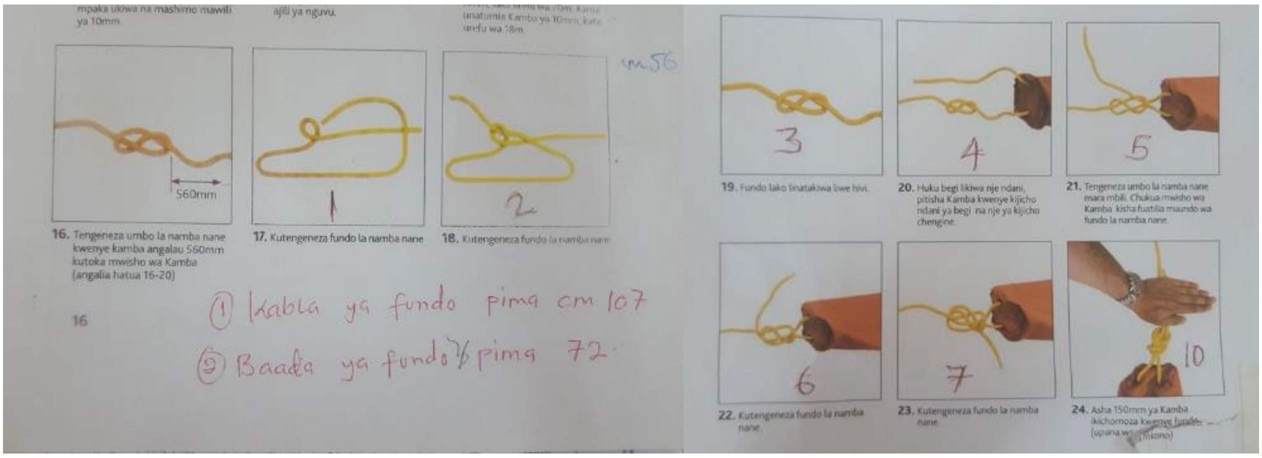


Figure 12: Studying the procedure for tying the knot as specified in the original instruction manual and identifying missing information between stages 7 and 10.

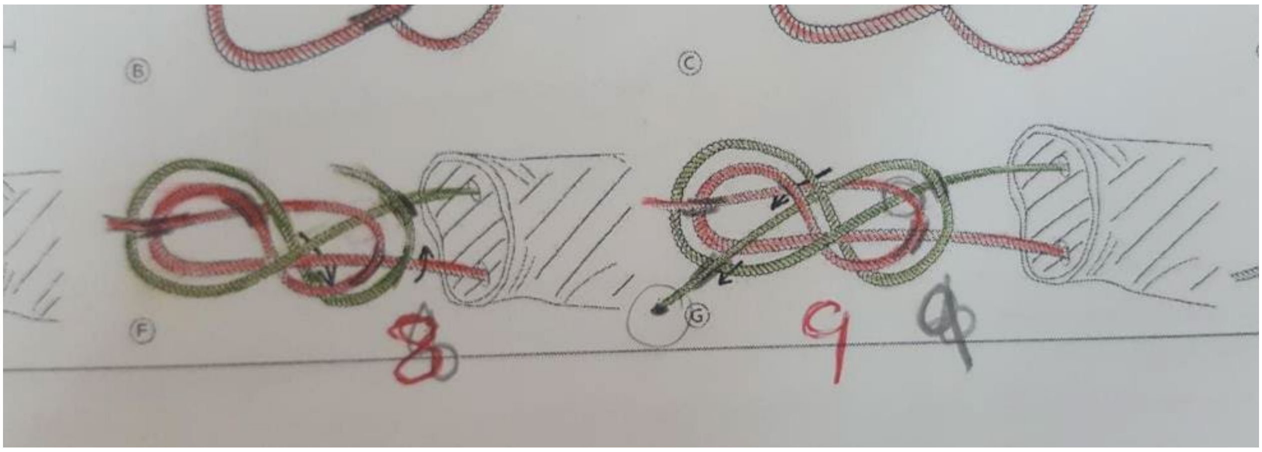


Figure 13: Clarifying the missing stages 8 and 9 using colour to distinguish between the two ends of the rope needed for tying the knot.

Conclusion

This study has shown how the transition from a human-centred design (HCD) approach to a participatory design and making approach that embraces the whole process of manufacturing low-cost rescue throwlines in Zanzibar, from sourcing materials in the market through to making and testing the product - the 'workflow system' - highlights the importance and value of context specific experiential knowledge. The study builds on suggestions by Conrad and Devall (2020) that opensource design tools for the community production of low-cost throwlines fell short of providing opportunities for experiential knowledge and feedback loops to benefit community uptake of the drowning prevention initiative. The making process had been translated into a set of codified instructions that assumed the knowledge could be transferred. Not including local makers' experiential knowledge in the design of the manufacturing process risked not only safety critical processes being resisted or rejected, but limiting the adoption of the products within the community managed water safety programme.

The 'workflow system' prototype draws from the expert knowledge of safety critical design contributed by the RNLI International HCD team, the tailors' local environmental knowledge, the experiential knowledge of design and making shared by the tailors and the research team, although from different positions of culture, race and privilege. By including the tailors in the creative practice of *problematisation* as well as the *problem-solving* process, a more environmentally and technologically appropriate guidelines and samples were produced to clarify difficult-to-make features which might occur within the process of small-batch production. An overall understanding was reached about how these additional components can be used alongside design tools such as the opensource low-cost production instruction manual as well as physical prototypes to form more holistic and comprehensive 'workflow system' that takes into account these experiential dimensions of intangible knowledge exchange.

This study has also highlighted that in order to enact change towards the community adoption and management of low-cost buoyancy aids, the tailoring community can play a vital role with their creative practice as mediators of design languages across institutional and cultural boundaries, whilst also negotiating technological and material networks. Developing the prototype 'workflow system' with the tailors at Pamoja demonstrates the complexity of knowledge exchange at play. As such, this creative design and making practice has been seen to engage expertise and knowledge from multiple disciplines (Nimkulrat et al, 2020). Not only is the knowledge from different disciplines (design, engineering, water safety, making) but it is of different types (practical, theoretical, environmental, experiential) and differently positioned (Euro-western, Indigenous Tanzania/Zanzibar).

One of the key questions we as researchers have asked ourselves over the course of this study has been to what extent, or how, might the results offer a generalised contextual replication of use to other communities. When considering this as a course of 'next steps' we need to return to one of the core aims of the study, which was to highlight the role of makers in the capacity building process for drowning prevention in Zanzibar. We argue that for this to be effective, an open and iterative 'workflow' system that continually responds to localised adaptation for capturing complex knowledge exchange is more appropriate for developing capacity-building than a new codified 'instruction tool'. It is crucial that contextual and local experiential knowledge can be easily adopted into the manufacturing process for it to be owned by the makers themselves. A codified (and therefore fixed) 'instruction tool' may lead to the replication of resistance or rejection in another setting. It is our intention to study how, or if, this 'workflow system' might be applied in a different setting, in Tanzania, as part of the next steps in this study, and to what degree the 'workflow system' developed needs to be adapted by a different community of makers to support this complex knowledge exchange process.

We recommend adopting an iterative methodological approach to innovation for managing complex knowledge exchange projects such as this; one that favours collaboration across disciplines *and* knowledge positions. The study elucidates some of the barriers for exchanging this critical experiential knowledge with stakeholders, but also exposes challenges for creating new social infrastructure within the community concerning drowning prevention that points towards continuing research:

- Understanding the context of different knowledge positions regarding design and manufacturing.
- Communicating alterations in the design that respond better to the environment.
- Developing confidence in experiential knowledge-based safety testing methods.

Acknowledgements

This study was funded by the Global Challenges Research Fund in 2021. We are sincerely grateful to our project partners at Pamoja Zanzibar: Josephina, Mwanahamis, Almish, Mwajuma, Zainab, Evelyne Teschner-Krug, Linda Kreitner and Nabil Mussa; and at the RNLI International team: John Powell, Tom Mecrow.

References

Berg, M. J. (2008). Experiential Knowledge. In L. M. Given (ed.) The SAGE Encyclopedia of Qualitative Research Methods. Thousand Oaks, CA: Sage. 321–322.

Bonnet, F., Leung, V. & Chacaltana, J. (2018). Women and men in the informal economy: A statistical picture (third edition). Geneva: International Labour Office [online] Available from https://www.ilo.org/global/publications/books/WCMS_626831/lang--en/index.htm (accessed 25 January 2023).

Bowen, S., Durrant, A., Nissen, B., Bowers, J. & Wright, P. (2016). The Value of Designers' Creative Practice within Complex Collaborations. Design Studies, 46, 174-198.

Conrad, F. & Devall, L. (2020). Drowning prevention by design: the semiotics of prototyping in low-resource environments – case study Zanzibar. Proceedings of the Sixth International Conference on Design Creativity, 26-28 August 2020, Oulu, Finland.

Cross, N. (2007). Designerly Ways of Knowing. Basel: Birkhäuser.

Dorst, K. (2011). The Core of "Design Thinking" and its Application, Design Studies, 32(6), 521-532.

Halskov, K. & Hansen, N.B. (2015). The diversity of participatory design research practice at PDC 2002–2012. International Journal of Human-Computer Studies, 74, 81-92.

Johansson‐Sköldberg, U., Woodilla, J. & Çetinkaya, M. (2013). Design thinking: past, present and possible futures. Creativity and innovation management, 22(2), 121-146.

Kara, H. (2018). Research Ethics in the Real World. Bristol: Policy Press.

Kaplinsky, R. (1990). The Economics of Small: Appropriate Technology in a Changing World. London: Immediate Technology Publications.

Manji, K., de Gruchy, T., Hanefeld, J., Vearey, J. & Walls, H. (2021). Using WhatsApp messenger for health systems research: a scoping review of available literature. Health Policy and Planning, 36, 774–789 2021.

Niedderer, K. (2007). Mapping the Meaning of Knowledge in Design Research. Design Research Quarterly, 2(2), 1–13.

Nimkulrat, N., Groth, C., Tomico, O. & Valle-Noronha, J. (2020). Knowing together – experiential knowledge and collaboration. CoDesign, 16(4), 267-273.

Pamoja Zanzibar (2023) Who we are. [online] Available from *https://www.pamojazanzibar.org/index.php/en/ (accessed 27th January 2023).*

Royal National Lifeboat Institution (2021). Our international work. [online] Available from https://rnli.org/what-we-do/international (Accessed 16th January 2023).

Sarrassat, S., Mrema, S., Tani, K., Mecrow, T., Ryan, D. & Cousens, S. (2019). Estimating drowning mortality in Tanzania: a systematic review and meta-analysis of existing data sources. Injury prevention: journal of the International Society for Child and Adolescent Injury Prevention, 25 (5) 459-471.

Sennet, R. (2008). The Craftsman. London: Allen Lane.

Smith, A., Fressoli, M., Abrol, D., Around, E. & Ely, A. (2017). Grassroots Innovation Movements. Abingdon: Routledge.

Tuhiwai Smith, L. (2021). Decolonizing Methodologies: Research and Indigenous Peoples (third edition). London: Zed Books.

Vines, J., Clarke, R., Wright, P., McCarthy, J. & Olivier, P. (2013). Configuring participation: on how we involve people in design. April 2013. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 429-438.

World Health Organisation (2014). Global report on drowning: preventing a leading killer. [online] Available from https://www.who.int/publications/i/item/global-report-on-drowning-preventing-a-leading-killer (Accessed 27th January 2023).

Dr Emma Shercliff

Dr Emma Shercliff is Associate Professor of Textiles and Participatory Making at the Arts University Bournemouth. With over 20 years' experience devising, participating in and leading creative workshops with various participants she has developed a focus on creative participatory research methodologies and participatory approaches to design, making and cultural engagement applicable to wider cross- and interdisciplinary research, knowledge exchange and consultancy settings. She is co-founder of the Stitching Together research network, which brings together researchers, professional textile practitioners, project commissioners and enthusiast textile maker groups to foster critical dialogue around participatory textile making in research and practice. Emma is a peer reviewer for various academic journals and co-editor of the Journal of Arts and Communities. Her current research addresses the development of community owned work-flow systems for the making of life-saving buoyancy aids in Zanzibar using a participatory workshop-based methodology with tailors, and the development of an evaluation framework for creative participatory making activities in research contexts.

Lucy Devall

I am an interdisciplinary researcher, interested in the roles design can play within the concept of innovation ecosystems. Alongside my work as the Innovation Lead at the global design and engineering consultancy, Buro Happold, I am also studying for a PhD in Design at Imagination Lancaster, a research unit of Lancaster University. Prior to undertaking this study, I worked for several years across east Africa with small business communities in Tanzania and Zanzibar unearthing the value of creative practice in complex knowledge exchange activities.

Franziska Conrad

Franziska is a Senior Teaching Fellow in Design at the University of Southampton teaching Design in a multi-disciplinary context to engineering students. She is a product designer and accomplished entrepreneur with 19 years' experience of design experience. She has a passion for Nature Inspired Design (NID) and has completed specialised Biomimicry training. Her PhD research is focussed on embedding NID in design education and enhancing students understanding of sustainable design practice.
Franziska is an active design thinker and strategist who has moved her traditional product design practice into the domains of speculative and systems design. She has ongoing research relationships with the Royal National Lifeboat Institution (RNLI). The focus here is on participatory design research in the context of drowning prevention in developing countries, including Zanzibar, mainland Tanzania and Bangladesh. She is also interested in the impact of gender within Product Design education.

The prototype-evaluation choreography

Eveline van Zeeland, University of Twente

Abstract

Prototyping and the acquisition of knowledge through evaluation are essential elements of the design process. However, both prototyping and evaluation are mostly studied separately. Moreover, prototyping and evaluation both suffer from conceptual confusion caused by the coexistence of many different perspectives brought forward by different disciplines. Multidisciplinarity is needed for innovative breakthroughs, but appears to be challenging. The goal of this paper is to offer a roadmap of possibilities to overcome these challenges and to build bridges between different perspectives in such a way that prototyping and evaluation can be structured, positioned, planned and executed coherently instead of separately. In this roadmap, the possible directions for the WHY, WHEN, WHAT, HOW and WHOM of both prototyping and evaluation are presented. The roadmap functions as a canvas, in which horizontal and vertical alignment of the different elements is crucial. Both a prototyping and an evaluation strategy must be carefully planned and aligned with each other. The presented roadmap assists in that process in such a way that multiple perspectives can strengthen each other. Only when choices about the WHY, WHEN, WHAT, HOW and WHOM of both prototyping and evaluation are made explicit, they can be discussed, communicated and learned from. In the end, prototyping and evaluation are like two dance partners that dance best if they harmoniously dance together. The choreographer designs and plans the dancing steps of the two dancing partners in such a way that a harmonious, elegant and inspiring dance is the result. The presented prototype-evaluation choreography in this paper helps the designer to be the choreographer of the prototyping and evaluation part of the design process.

Prototyping, Evaluation, Conceptual confusion, Alignment

“It takes two to tango”. Al Hoffman & Dick Manning (1952)

Prototyping is a key element of the design process. It is even stated that prototyping is critical for successful innovation (Camburn, et al., 2017; Brown, 2019). Prototyping and the evaluation of prototypes go hand in hand, at least if you follow the reflective practitioner perspective (Schön, 1983). What is the value of a prototype if it is not evaluated in some kind of way? How can one acquire knowledge from a prototype without evaluation? Although it is not more than obvious that prototyping and evaluation go hand in hand, this appears to be difficult sometimes. That has two main reasons. First, there exists conceptual confusion around the topics of both prototyping and evaluation, and, second, both prototyping and evaluation are executed by scientists and practitioners from different disciplines. These two reasons are related: the multidisciplinarity contributes to the conceptual confusion. Some scientists and practitioners have a design background and others don’t. Designers typically focus on the creation of what does not exist yet, whereas non-designers are focused on what already exists (Johansson-Sköldberg, Woodilla, & Çetinkaya, 2013; Martin, 2007). This difference in perspective creates complications.

A factor that increases the complexity of bridging different perspectives on prototyping and evaluation in an effective way, is the evolution that has occurred the past decades regarding the concept of prototyping. Nowadays, prototyping is not only used in the design process of material artefacts, like products or buildings, but also in the development process of large and complex systems or to explore and develop brand new concepts (Camburn, et al., 2017). Furthermore the landscape of prototyping is changing due to new technical possibilities like generative AI, 3D-printing or Virtual, Augmented or Mixed Reality. Due to the increased popularity and acceptance of design thinking and design science research, the scope in which prototyping is practiced has enlarged and changed. Of course this has an effect on the evaluation of prototypes as well.

Another complicating factor is that the translation from prototype to knowledge, for which the evaluation process is critical, often remains unclear. Camburn et al state: "*A clearer understanding of quantified information gained from a prototype is needed"* (Camburn, et al., 2017, p. 25). Pries-Heje et al (2008) state with respect to evaluation: "*its importance is widely recognized, yet it is often poorly performed and there is little guidance … concerning how to choose and design an appropriate evaluation strategy"* (Pries-Heje, Baskerville, & Venable, 2008, p. 11). Winter claims that there is a "*lack of commonly accepted, specific evaluation guidelines for the different artefact types"* (Winter, 2008, p. 471). Because of this lack of guidelines and standards it is harder to trust the outcomes of the design process (Prochner & Godin, 2022).

Perhaps due to these difficulties, the academic literature is concentrated either around prototyping or around evaluation, but hardly around a combination of the two. Prototyping and evaluation are like a dance with two dance partners. However, if you don't understand each other's dancing styles and accompanying dancing steps, you will step on each other's toes. To design a beautiful dance, you must understand the differences in dancing styles, witness the evolution of the dance and see the possibilities of the different dancing steps. The purpose of this paper is to create this understanding. By presenting a roadmap of possibilities, this paper hopes to contribute to create bridges, not only between prototyping and evaluation, but also between different perspectives on the two concepts. In this paper the many faces of prototyping are discussed first, and are then followed by the many faces of evaluation. For both prototyping and evaluation there is elaborated on the WHY, WHEN, WHAT, HOW and WHOM. The resulting perspectives are combined in a roadmap of possibilities.

The many faces of prototyping

"*The best prototype is one that, in the simplest and most efficient way, makes the possibilities and limitations of a design idea visible and measurable"* (Lim, Stolterman, & Tenenberg, 2008, p. 3). This definition, showing the economic principle of prototyping, seems straightforward. However, the concept of prototyping is suffering from conceptual confusion: "*definitions differ widely and a common understanding does not exist among or within the disciplines"* (Exner, Lindow, Stark, Ängeslevä, & Bähr, 2015, p. 2). This conceptual confusion already starts with the question what a prototype entails. Some see sketches and drawings as prototypes, whereas others distinguish prototypes from sketches and drawings (Pei, Campbell, & Evans, 2011; Hannah, Joshi, & Summers, 2012). The same holds for models: they can be seen as different from prototypes or they can be seen as a type of prototype. Since prototypes can be perceived as a concept, an approach, a method and a technology (Exner, Lindow, Stark, Ängeslevä, & Bähr, 2015; Yu, Pasinelli, & Brem, 2018), they can have different shapes and forms: a drawing, a model, a sketch model, a prototype model, a 3D prototype, et cetera. Within this paper we take a broad perspective on prototyping, and include every technique, shape and form, as long as the prototype "*makes the possibilities and limitations of a design idea visible and measurable"* (Lim, Stolterman, & Tenenberg, 2008, p. 3). Figure 1 shows an overview of this broad perspective on prototyping with different examples, based on different forms, techniques and materials, within this broad range.

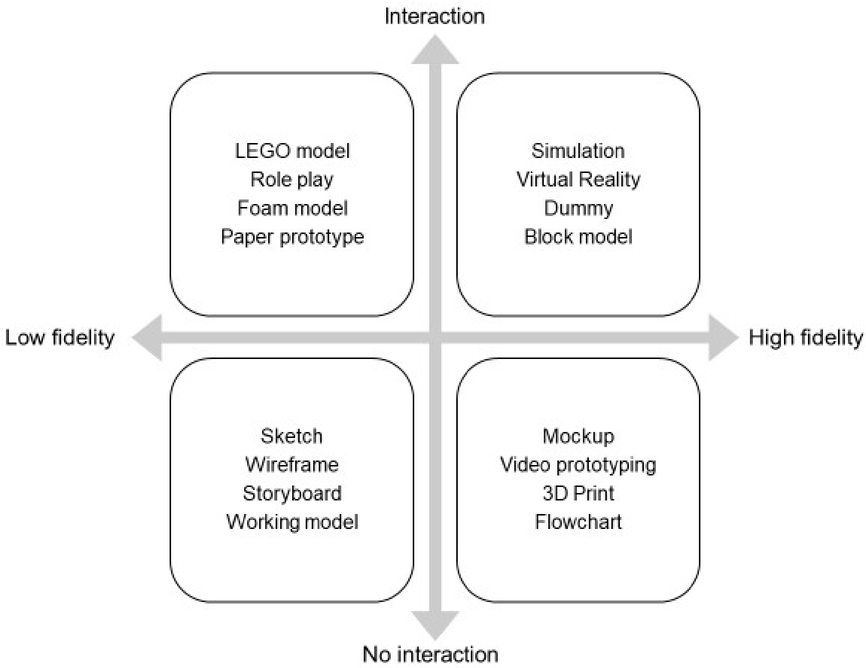


Figure 1: Prototype examples in a positioning map, where fidelity refers to the level of truthfulness to reality and interaction to the ease at which users can interact with the prototype (adjusted from Van Zeeland, 2023)

Taxonomies of prototypes have been suggested with respect to the WHY, WHEN, WHAT, HOW and WHOM of prototyping. With respect to the WHY, there are two groups of prototypes: 1) prototypes that nourish the design process and 2) prototypes that serve as a medium to communicate and test the artefact, see figure 2. Buchenau and Suri (2000) summarize these two groups as ‘design process’ versus ‘design decision’. Regarding this design process there are three possible routes: an explorative route, an experimental route and an evolutionary route (Floyd, 1984; Exner, Lindow, Stark, Ängeslevä, & Bähr, 2015). When prototypes nourish the design process, they don’t have to reflect the possible final design, but can also entail a feature of the design that one wants to explore. Prototyping is than done with the objective of refinement, exploration or active learning (Camburn, et al., 2017). When prototypes serve as a medium to communicate and test the artefact, the prototype mostly is “*a pre-production representation of some aspect of a concept or final design”* (Camburn, et al., 2017, p. 1). When the prototype is a medium to communicate the objective is to *share* information; when the prototype is a medium to test the objective is to *acquire* information.

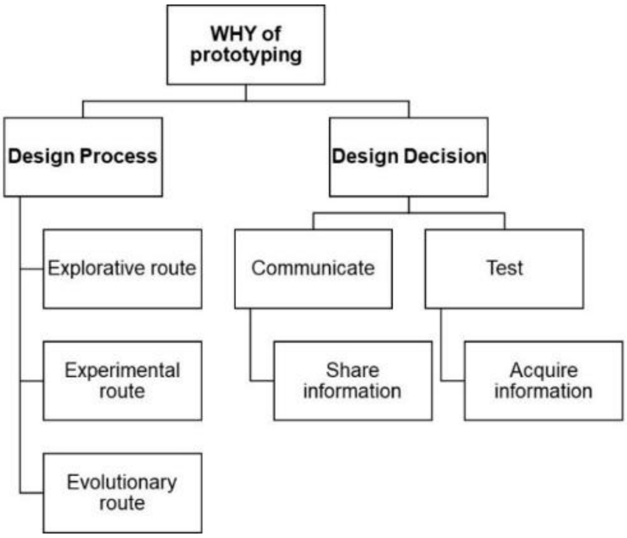


Figure 2: Different purposes of prototyping

Regarding the WHEN, the perspective on prototyping changes when in the design process one is prototyping. Exner et al (2015) define three phases: 1) clarification of the task, 2) conception of the idea, and 3) design of the concept, and this process is not really debated. In early stages of the design process, prototypes are predominantly explorative by nature, whereas further in the design process prototypes are more often used to evaluate the concept, principles or requirements (Exner, Lindow, Stark, Ängeslevä, & Bähr, 2015). The WHEN and WHY are thus closely related.

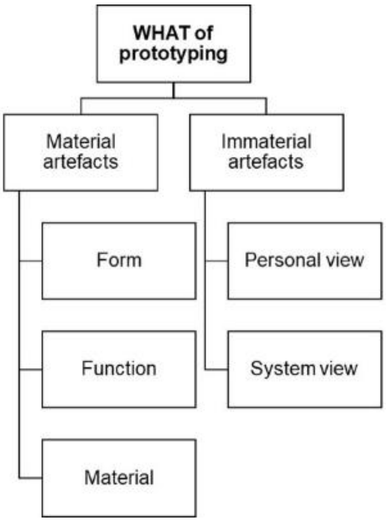


Figure 3: The WHAT of prototyping and its different pillars

With respect to the WHAT, it is first important to define the scope of what the prototype covers: the level of inclusiveness (Lim, Stolterman, & Tenenberg, 2008) and to make the type of prototype explicit. For the development and evaluation of the prototype it is important to make the difference between a material and immaterial artefact explicit. There are different taxonomies of prototypes of material artefacts and the dominant pillars are form, function and material (Camburn, et al., 2017; Exner, Lindow, Stark, Ängeslevä, & Bähr, 2015). When talking about prototypes of immaterial artefacts other considerations may be relevant. In this context the difference between artefacts with a personal view, where the artefact changes the nature of the task the person is facing, or artefacts with a system view, where the artefact enhances the performance of a system, is relevant

(Rabardel & Waern, 2003; Norman, 1991). The different pillars that can constitute the WHAT of prototyping are visible in figure 3.

With respect to the HOW, one can see the most common ground based on which prototypes are categorized: the level of fidelity. However, the concept of fidelity suffers from conceptual confusion as well: does it refer to the level of functionality, the level of visual polish, or the level of interactivity (McCurdy, Connors, Pyrzak, Kanefsky, & Vera, 2006)? Since the level of functionality, visual polish and interactivity have an enormous effect on the evaluation of the prototype, it is important to make choices about this explicit. A positioning map with axes based on which the prototype is positioned (see figure 1 for an example) can be of help here. The HOW relates back to the WHY: low-fidelity prototypes are useful in the design process, when one tries to see possibilities and problems, and high-fidelity prototypes come into place when management has to make an investment decision (McCurdy, Connors, Pyrzak, Kanefsky, & Vera, 2006).

With respect to the WHOM, this relates to 'for whom' one is prototyping; it relates to the audience for whom the prototype is created (Buchenau & Suri, 2000). Different groups can be identified here based on three levels: 1) the design level (the design team or designer), 2) the decision making level (the investor or the manager) and 3) the user level (the individual client or user population).

Most of the choices regarding the WHY, WHEN, WHAT, HOW and WHOM are implicitly made. Because of that, confusion is lurking. It is important for the design process to make the choices about the WHY, WHEN, WHAT, HOW and WHOM explicit. Only when choices are made explicit, they can be discussed, communicated and learned from.

The many faces of evaluation

"*Evaluation is what puts the 'science' in 'design science'*" (Venable, Pries-Heje, & Baskerville, 2012, p. 425). Evaluation is a crucial element of every design process (Pries-Heje, Baskerville, & Venable, 2008; Hevner, March, Park, & Ram, 2004). Despite its relevance and importance, specifically for knowledge creation, evaluation is often poorly performed and there is relatively little guidance in how to evaluate (Pries-Heje, Baskerville, & Venable, 2008). Furthermore, different perspectives on evaluation suffer from conceptual confusion. For example, Lim, Stolterman and Tenenberg (2008) distinguish evaluation from design exploration, whereas others see design exploration as a possible manifestation of evaluation. One factor that complicates the process of evaluation is that, with a few exceptions, the evaluation cannot take place in the actual situation, because it is the purpose of the design to create a new situation. Because of this complication, the standards and requirements that are used for evaluation in the social and natural sciences, are not applicable here. A different type of knowledge, prescriptive instead of descriptive, requires a different evaluation strategy (Sonnenberg & vom Brocke, 2012).

Also with respect to evaluation the WHY, WHEN, WHAT, HOW and WHOM can be disentangled. Venable et al (2012) distinguish five WHY's with respect to the evaluation process: 1) evaluate an instantiation of a designed artifact to establish its utility and efficacy (or lack thereof) for achieving its stated purpose (in other words: how well the artifact performs), 2) evaluate the formalized knowledge about a designed artifact's utility for achieving its purpose (for example design principles or technological rules), 3) evaluate a designed artifact or formalized knowledge about it in comparison to other designed artifacts' ability to achieve a similar purpose (does the new artifact provide greater relative utility than existing artifacts?), 4) evaluate a designed artifact or formalized knowledge about it for side effects or undesirable consequences of its use, and 5) evaluate a designed artifact formatively to identify weaknesses and areas of improvement for an artifact under development. The five WHY's operate at the design process level, and thus are relating to the first WHY of prototyping: nourishing the design process. With respect to the second WHY of prototyping, serving as a medium to communicate and test the artefact (making a design decision), the WHY of evaluation is important for the decision between implementing, retesting, adapting or redesigning the artefact (Zeeland, 2023). Figure 4 presents an overview of the different purposes of evaluation.

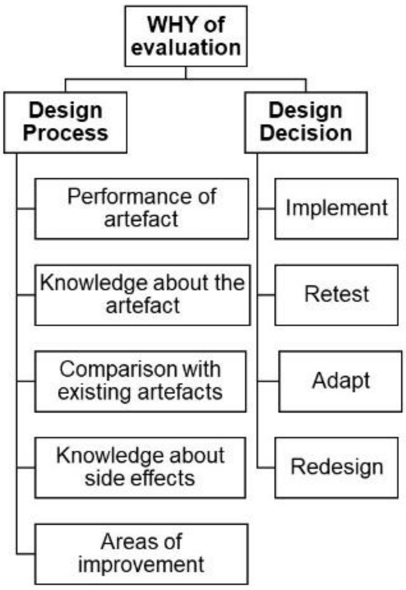


Figure 4: Different purposes of evaluation

With respect to the WHEN, the dominant taxonomy in evaluation is ex ante versus ex post evaluation; in other words, before or after the implementation of the artefact. Another relevant aspect regarding the WHEN is the process of evaluation. Some see evaluation as a separate step in the process towards implementation, and might use a 'stage-gate-model' in which designers first build and then evaluate. For example, within the interpretation of design thinking by Stanford Design School the Test-phase, or evaluation-phase, is the last step in the process. Others see evaluation as a cyclic process of continuous reflection, for example the BIE-cycles: Building – Intervention – Evaluation (Sein, Henfridsson, Purao, Rossi, & Lindgren, 2011).To return to the choreography metaphor: does first one dancer move and then the other or do you dance together?

When discussing the WHAT of evaluation, one gets to the core question of what design actually is: 'creating artefacts' or 'creating meaning'? As Johansson-Sköldberg, Woodilla and Çetinkaya elegantly compare the economical perspective of Herbert Simon with the philosophical perspective of Klaus Krippendorff: "*For Simon the artefact is at the core, and he would probably say that meaning is an attribute, while for Krippendorff meaning is the core of the design process and the artefact becomes a medium for communicating these meanings"* (Johansson-Sköldberg, Woodilla, & Çetinkaya, 2013, p. 126). Almost every paper on evaluation does *not* discuss this type of WHAT. In most papers the WHAT is covered by the evaluation criteria. However, what it is that has to be evaluated is a relevant question to be answered before one can set evaluation criteria. To answer that question, the difference between object and attribute is relevant. Most objects, both physical as non-physical, are consisting of different attributes. According to Rossiter (2002), objects should be judged based on these attributes. For example, if a new hotel concept is designed, people will describe this new concept using different attributes. Some will perhaps focus on traits as 'calming and relaxing', others might focus on possibilities for interaction or on the 'look and feel'. These are all different attributes, and all different levels on which the evaluation takes place. Each attribute is covered by one or more evaluation criteria. The papers that discuss evaluation criteria, mostly relate these criteria to the complete object. For example, Checkland and Scholes (1990) identify the five E's: efficiency, effectiveness, efficacy, ethicality and elegance. However, elegance, for example, will possibly relate to one or some attributes of the object, but probably not to all. These kind of lists of evaluation criteria implicitly assume that every object has the same set of attributes that can be evaluated with the same set of criteria. However, evaluation criteria actually should form an explicit choice of the design team (Sonnenberg & vom Brocke, 2012). Each attribute of the artefact can be evaluated with one or more evaluation criteria that are set specifically for that attribute or all the attributes can be evaluated based on the same set of criteria. These possibilities are described in figure 5.

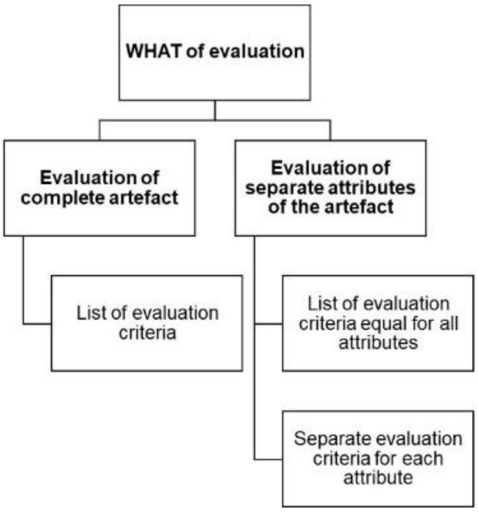


Figure 5: Evaluation strategies and evaluation criteria

The WHEN and WHAT are closely related. With ex ante evaluation mostly other evaluation criteria are used than with ex post evaluation (Pries-Heje, Baskerville, & Venable, 2008). But the WHAT is also strongly related to the WHY of prototyping. If prototyping is used to nourish the design process, other evaluation criteria are used than when prototyping is used to make a decision about the design outcome (Pries-Heje, Baskerville, & Venable, 2008). For example an explorative objective of prototyping will lead to an evaluation of requirements, an experimental objective will lead to an evaluation of particular solutions and an evolutionary approach will evaluate both requirements and solutions (Floyd, 1984; Schneider, 1996). The WHAT also relates to the WHOM of prototyping. When prototypes are made for users, the WHAT of evaluation gets more complex because there is a double character to be evaluated: "*they contain components from artefacts themselves, and components from users' utilization schemes"* (Rabardel & Waern, 2003, p. 643). The evaluation of the prototype than entails two dimensions: how it is designed and how it is or can be used.

The HOW of evaluation entails a lot, see figure 6. Most literature concerning evaluation deals with the HOW, specifically the possible methodologies. For example Hevner et al (2004) distinguish observational, analytical, experimental, testing and descriptive design evaluation methods. Besides the methodology, the evaluation approach is relevant as well. In their strategic Design Science Research Evaluation Framework, Venable, Pries-Heje and Baskervill (2012) distinguish between naturalistic evaluation and artificial evaluation. Also the depth of the evaluation is an element to think about. Peffers et al observe two levels: 1) the level of demonstration, which is like a 'light-weight' evaluation, and 2) the level of evaluation, which is a more formal level of evaluation (please note the created conceptual confusion around the term 'evaluation' here) (Venable, Pries-Heje, & Baskerville, 2012; Peffers, et al., 2006). Another relevant element of the HOW is the question how you deal with the information acquired by the evaluation. Bannister and Remenyi (2000) distinguish between a positivist/reductionist approach and a hermeneutic approach. For the positivist/reductionist approach you allow the methodology to make the decision; you let the data speak for itself. For the hermeneutic approach there is room for interpretation, intuition and 'gut feeling'; the professional acts upon his understanding of the data. With respect to the HOW, of course also the procedure is relevant. Pries-Heje et al (2008) propose a four-step procedure: 1) analyze the context of the evaluation and define the evaluation requirements, 2) match the needed contextual factors of the evaluation (step one) to evaluation criteria, 3) select an appropriate evaluation method, and 4) design the evaluation in detail. However, if you look at the process of evaluation in a bigger context, as in how the evaluation should lead to knowledge, a lot of different procedures are proposed in academia (Winter, 2008).

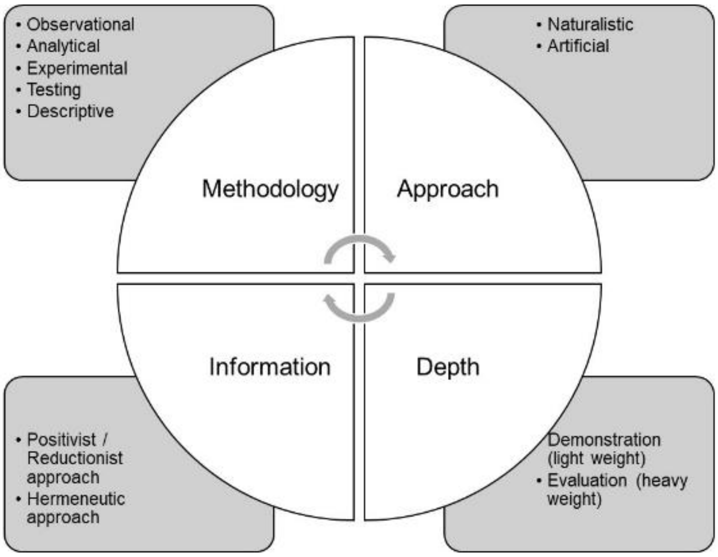


Figure 6: The HOW of evaluation

When evaluating, the WHOM means 'by whom' or 'as perceived by', which is also called the 'rater identification' (Rossiter, 2002). The evaluation *per definition* is dependent on the rater, and should therefore always be made explicit. There are four types of raters: 1) the designers themselves, 2) the decision makers, 3) the users, and 4) experts or peers. The type of evaluation is depending on who is rating. For prototypes that are built to nourish the design process, the designer or researcher is mostly the dominant actor in the evaluation process; for prototypes that serve as a medium to communicate and test the artefact, the user or decision maker are mostly the dominant actors.

Prototype-evaluation roadmap

In this section the different perspectives regarding the WHY, WHEN, WHAT, HOW and WHOM of both prototyping and evaluation are combined in a roadmap of possibilities. A roadmap is different than a framework: a framework defines how one *should* do things, a roadmap shows how one *could* do things. Within this roadmap every prototype is considered to be unique: "*each prototyping effort requires a certain unique strategy to resolve a design problem or opportunity"* (Camburn, et al., 2017, p. 2). Camburn et al (2017) claim that a prototyping strategy should be carefully planned, which is also the case for the evaluation strategy. The roadmap in figure 7 is designed to assist in the planning of these strategies and to make all the choices along the way explicit and coherent.

The roadmap functions as a canvas, in which each empty cell is unique. Each empty cell reflects the choice made in that specific step along the way. However, the ten different cells are not independent, but strongly relate to each other. Therefore the prototype and evaluation strategy should be aligned on two levels. First of all there should be a *horizontal fit* of the different cells in each row: the WHY, WHEN, WHAT, HOW and WHOM should together make a logical and coherent strategy. For this horizontal fit, prototyping and evaluation are judged separately. Second, there should be a *vertical fit*, bridging the world of prototyping with the world of evaluation. Using the choreography metaphor, the horizontal fit deals with the question how well each dancing partner can dance, and the vertical fit with the question how well they dance together. Design teams should change the completion of each cell as long as that change improves the vertical and/or horizontal fit of the different elements of the roadmap.

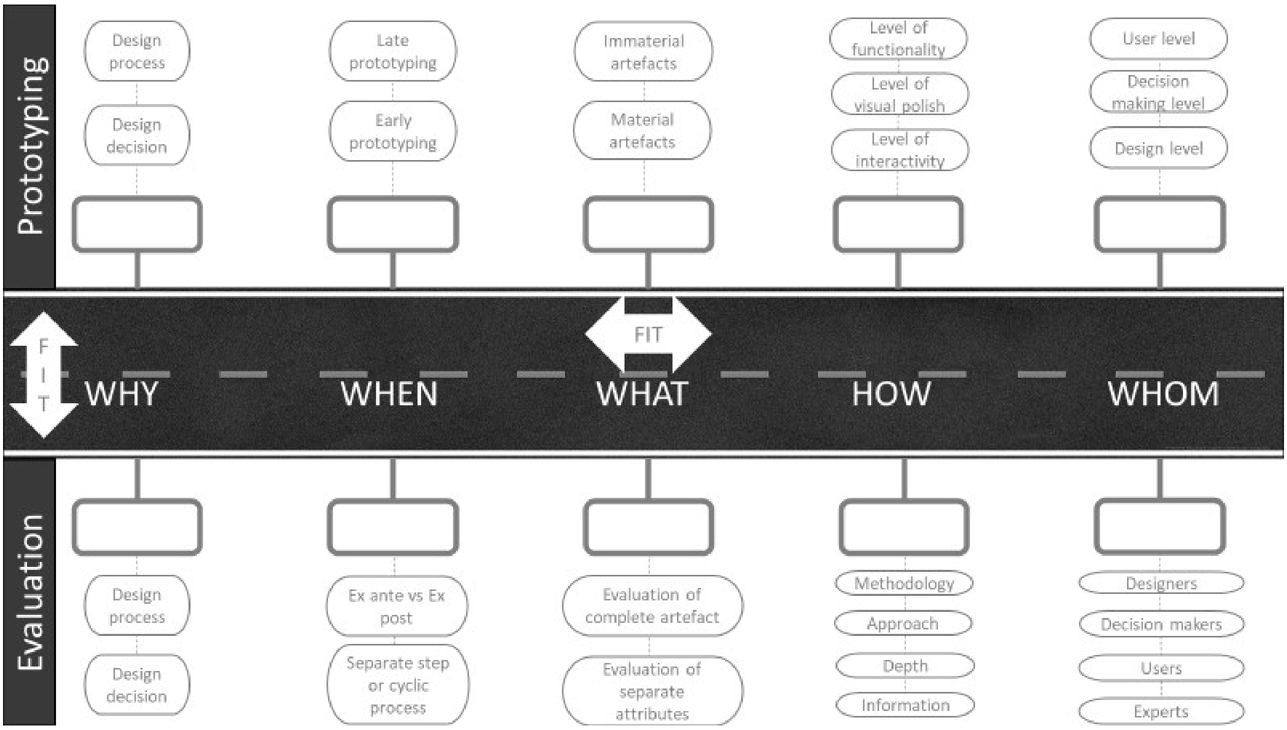


Figure 7: The prototype-evaluation roadmap

Discussion and conclusion

"*Just as a picture can be worth a thousand words (if you know what it depicts), a prototype can substitute for volumes of paper documents – if, and only if, you know what it is supposed to tell you"* (Schneider, 1996). The bridge from prototyping to knowledge is paved by evaluation. Prototyping and evaluation go hand in hand. One can only derive insights and knowledge from a prototype if one evaluates the prototype. Both prototyping and evaluation can be done from different perspectives. Most papers are concentrating on these perspectives either with respect to prototyping or with respect to evaluation. This paper tries to bridge those two worlds.

To bridge the two worlds of prototyping and evaluation one has to be conscious about what constitutes those two worlds. The presented roadmap might help in creating this consciousness. If the evaluation and the acquired knowledge remains in the head of the designer, which is often the case, than the knowledge is lost if the designer is not attached to the project anymore. Documentation of the evaluation and the acquired knowledge is therefore important. Not every artefact leads to knowledge in a broader context; that is only the case if the artefact is generic to some extent (Winter, 2008). A structured way of planning and assessing prototypes and their evaluations, will also help the communication process around the design and the acquired knowledge during the design process. There is often a lack of formality in the process of synthesis, that causes vagueness around the design process and its results (Kolko, 2010; Rutkowska, Sleeswijk Visser, & Lamas, 2019). Making the steps taken towards synthesis more explicit, will help others to understand.

The presented roadmap functions as a canvas in which each empty cell reflects one or more elements to think about and to plan. It is remarkable that one of the most important elements of the roadmap for the creation of knowledge, the WHAT of evaluation, is in practice mostly not made explicit or even considered. Probably that is because this is one of the most difficult steps to take (Rossiter, 2002). Within the canvas every empty cell must be made explicit. So when using the canvas, one will not oversee one of the most important elements in the evaluation of prototypes.

The roadmap serves to help the design team to align the different dance moves with each other. It helps to assess whether there is both a horizontal and a vertical fit between the different cells in the canvas. To judge whether or not this fit is there, both logic and intuition are important. To discover blind spots it helps to ask others for peer consultation. Peer consultation should be a standard step in the design of the prototyping and evaluation strategy. Another aspect where peer consultation is important, is to sharpen the eye on the ethical perspective. Every design has impact, and designers can be considered as change agents. Creating change comes with a responsibility. With respect to the prototyping-evaluation dance, this responsibility underlines the importance of evaluating possible side effects or undesirable consequences of the use of the artefact (Venable, Pries-Heje, & Baskerville, 2012). As Tim Brown, brings forward: "*Design thinking is not 'the invisible hand'. It is intentional. … If we design social media applications to be enticing and addictive, then we are doing so because we wish for that outcome. If we don't wish what we get, then we are being very poor designers. Design thinkers have a responsibility to understand the outcomes they are designing for and to be conscious about the choices they are making"* (Brown, 2019, p. 4). Including independent peers helps to increase the consciousness throughout the decision process.

Choices in the roadmap affect the dynamics of the process. For example, a higher level of fidelity has an impact on the reactions given by the actors reflecting on the design (Hannah, Joshi, & Summers, 2012). Buchenau and Suri state that "*the tools we use to design, such as prototypes, influence the way we think*" (Buchenau & Suri, 2000, p. 425). About this dynamic relationship between prototyping, evaluating and creating knowledge we don't know that much, and should be the topic for future research.

What also remains for future research is the impact of context variables on the choices in the roadmap. For example social, organizational and cultural dimensions might impact the choices to be made (Rabardel & Waern, 2003; Sonnenberg & vom Brocke, 2012). Another context variable that has an impact is the set-up of the design team and whether or not one can speak of participatory design. But also technological aspects and developments within the design discipline will affect the choices to be made. The world of prototyping is changing due to new technological possibilities (for example 3D-printing, AI generated prototypes or VR simulations) and new situations in which prototyping is used. This evolution of prototyping is not affecting the roadmap itself, but will affect the choices to be made. Also on the evaluation side evolution takes place. For example, the availability of new evaluation methods, such as fMRI or EEG, might change the choices to be made in the roadmap (Hay, Duffy, Gilbert, & Grealy, 2022).

Some uses of evaluation are under addressed in this paper because they lie beyond its scope. One example is the evaluation of design oriented projects by others, for example teachers who evaluate the design process of their students. For these type of evaluations, the CCP-model by Symons (1991) is suggested. With the CCP-model you base your evaluation on three elements: Context, Content and Process. Since this type of external evaluation lies beyond the scope of this paper, these type of evaluation criteria are not discussed here, although it is worthwhile to elaborate on this perspective for future research, because it is relevant when judging each other's work, which might occur in the context of publication and collaboration.

Prototyping only supports interconnections and collaboration among researchers and practitioners if professionals from different disciplines truly understand each other and are not burdened by conceptual confusion. If you learn about each other's dancing styles and dancing steps, than one is able to design new dancing combinations together. This paper hopes to contribute to a more *inclusive evaluation* in which multiple perspectives strengthen each other.

If you see a dance as a total concept, you can tell whether you think the dance is beautiful or not; if you are aware of the different dancing steps that make the total dance, you can say something about the quality of the dance. So to be able to evaluate the many faces of prototyping, you need to understand these different steps. If you can appoint them separately, you can also point them out to others. The here presented roadmap is meant as a prompting board to ease this process of pointing out. The more articulated the dancing steps are (i.e. the more the prototyping and evaluation choices are made explicit) and the more beautiful the interplay of the two dance partners is (i.e. the more coherent prototyping and evaluation is planned and executed), the better the dance.

References

Bannister, F., & Remenyi, D. (2000). Acts of faith: instinct, value and IT investment decisions. *Journal of Information Technology, 15*(3), 231-241.

Brown, T. (2019). *Change by design - revised and updated.* New York: HarperCollins Publishers.

Buchenau, M., & Suri, J. (2000). Experience prototyping. *Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques*, (p. 424-433).

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., . . . Wood, K. (2017). Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science, 3*(13), 1-33.

Checkland, P., & Scholes, J. (1990). *Soft Systems Methodology in Practice.* Chichester: Wiley.

Exner, K., Lindow, K., Stark, R., Ängeslevä, J., & Bähr, B. (2015). A transdisciplinary perspective on prototyping. *Exner, K., Lindow, K., Stark, R., Ängeslevä, J., Bähr, B., & Nagy, E. (2015, June). A transdisciplinary perspIEEE international conference on engineering, technology and innovation*, (p. 1-8).

Floyd, C. (1984). A systematic look at prototyping. In R. Budde, & e. al, *Approaches to prototyping.* Berlin: Springer.

Hannah, R., Joshi, S., & Summers, J. (2012). A user study of interpretability of engineering design representations. *Journal of Engineering Design, 23*(6), 443-468.

Hay, L., Duffy, A., Gilbert, S., & Grealy, M. (2022). Functional magnetic resonance imaging (fMRI) in design studies: Methodological considerations, challenges, and recommendations. *Design studies, 78*(C), 1-32.

Hevner, A., March, S., Park, J., & Ram, S. (2004). Design science in Information Systems research. *MIS Quarterly, 28*(1), 75-105.

Johansson-Sköldberg, U., Woodilla, J., & Çetinkaya, M. (2013). Design Thinking: Past, Present and Possible Futures. *Creativity and Innovation Management, 22*(2), 121-146.

Kolko, J. (2010). Abductive thinking and sensemaking: the drivers of design synthesis. *Design Issues, 26*(1), 15-28.

Lim, Y., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes: prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction, 15*(2), 7: 1-27.

Martin, R. (2007). Design and business: why can't we be friends? *Journal of Business Strategy, 28*(4), 6-12.

McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., & Vera, A. (2006). Breaking the fidelity barrier: an examination of our current characterization of prototypes and an example of a mixed-fidelity success. *CHI 2006 Proceedings Usability Methods*, (p. 1233-1242). Montréal, Canada.

Norman, D. (1991). Cognitive artefacts. In J. Caroll, *Designing Interaction.* Cambridge University Press.

Peffers, K., Tuunanen, T., Gengler, C., Rossi, M., Hui, W., Virtanen, V., & Bragge, J. (2006). The design science research process: a model for producing and presenting information systems resarch. *1st International Conference, DESRIST 2006 Proceedings*, (p. 83-106).

Pei, E., Campbell, J., & Evans, M. (2011). A taxonomic classification of visual design representations used by industrial designers and engineering designers. *Design Journal, 14*(1), 64-91.

Pries-Heje, J., Baskerville, R., & Venable, J. (2008). Strategies for Design Science Research evaluation. *ECIS 2008 Proceedings*, *87.*

Prochner, I., & Godin, D. (2022). Quality in research through design projects: recommendations for evaluation and enhancement. *Design Studies, 78*(C), 1-26.

Rabardel, P., & Waern, Y. (2003). Editorial: From artefact to instrument. *Interacting with computers, 15*, 641-645.

Rossiter, J. (2002). The C-OAR-SE procedure for scale development in marketing. *International Journal of Research in Marketing, 19*, 305-335.

Rutkowska, J., Sleeswijk Visser, F., & Lamas, D. (2019). Towards actionable forms of communicating and sharing design knowledge. *EKSIG 2019 - Knowing together, experiential knowledge and collaboration*, (p. 252-277). Estonian Academy of Arts.

Schneider, K. (1996). Prototypes as assets, not toys - Why and how to extract knowledge from prototypes. *Proceedings of ICSE - 18*, (p. 522-531).

Schön, D. (1983). *The reflective practitioner: How professionals think in action.* Cambridge, MA: Basic Books.

Sein, M., Henfridsson, O., Purao, S., Rossi, M., & Lindgren, R. (2011). Action Design Research. *MIS Quarterly, 35*(1), 37-56.

Sonnenberg, C., & vom Brocke, J. (2012). Evaluation patterns for Design Science Research artefacts. In M. Helfert, & B. Donnellan, *Practical aspects of design science* (p. 71-83). Berlin Heidelberg: Springer-Verlag.

Sonnenberg, C., & vom Brocke, J. (2012). Evaluations in the Science of the Artificial; Reconsidering the Build-Evaluate pattern in Design Science Research. In K. Peffers, M. Rothenberger, & B. Kuechler, *Design Science Research in Information Systems* (p. 381-397). Berlin Heidelberg: Springer-Verlag.

Symons, V. (1991). A review of information systems evaluation: content, context and process. *European Journal of Information Systems, 1*(3), 205-212.

Venable, J., Pries-Heje, J., & Baskerville, R. (2012). A comprehensive framework for evaluation in Design Science Research. In K. Peffers, M. Rothenberger, & B. Kuechler (A cura di), *International Conference on Design Science Research in Information Systems. Design Science*

Research in Information Systems. Advances in Theory and Practice, p. 423-438. Berlin: Springer.

Winter, R. (2008). Design science research in Europe. *European Journal of Information Systems, 17*, 470-475.

Yu, F., Pasinelli, M., & Brem, A. (2018). Prototyping in theory and in practice: A study of the similarities and differences between engineers and designers. *Creativity and Innovation Management, 27*, 121-132.

Zeeland, E. (2023). *Getting started with Design Thinking.* FLOOT.

BIO Eveline van Zeeland

Dr. Eveline van Zeeland is Assistant Professor Design & Marketing at the chair of Product-Market Relations at the University of Twente (Faculty of Engineering Technology, Department of Design, Production and Management). Eveline has a background in Economics and Psychology and the (choice)behavior of people always plays a central role in her work. Her research interests are Designing for Trust, Innovation, Design thinking and Consumer neuroscience. Besides her academic work, Eveline is the author of multiple well received books, of which one, '*Marketing Design*', won the price for best marketing book of the Netherlands (2020).

Track 10: Mobility and Transportation

- The social role of a motorcycle prototype in fostering collaboration in a self-guided team of students

- Proto-flighting in the wild: a creative technologist approach to drone prototyping

- DIY Bus: Exploring Boundary Objects in Participatory Design Research

- Using machine learning as a material to generate and refine aircraft design prototypes

The social role of a motorcycle prototype in fostering collaboration in a self-guided team of students

Azul Amadeo, Politecnico di Milano
Francesca Mattioli, Politecnico di Milano, Department of Design

Abstract

Objects have shaped human societies and the interaction between subjects; they permitted to increase in relationship complexity. Objects' role became so significant that it impacts subject-to-subject communication creating a common ground to enhance understanding. To achieve it, objects stretch their meaning outside their usefulness, evolving alongside the surrounding context and subjects; they acquire stratified meanings depending on how subjects engage with them. Precisely, this research analyses the social role of objects in a design process to leverage communication between students from different cultural backgrounds and fields of knowledge. Such objects establish abstract communication channels via a material infrastructure to improve brainstorming in designing and developing two racing motorcycle prototypes. The study highlights how students implement their competencies to enhance project goals promoting collaboration awareness between workgroups and designing related components. The goal is to understand how objects' roles influence communication and subject-to-subject relationships to develop more integrated project solutions.

Self-guided project-based learning; students collaboration; social role of objects; boundary objects; prototypes

Learning design often entails learning by doing; hence, design education consistently relies on constructive learning methods, such as group projects guided by students with the supervision of the teaching staff (Mattioli, 2022). Design competencies are developed through solving problems by setting goals shared by the whole workgroup and the teacher. Such an approach implies that the learners actively participate in the learning process, collaborating to achieve shared goals. The teachers' roles might vary, but generally, they represent a guiding figure regarding the project and the learning process. However, students' self-guided projects also exist; in this case, groups of students are entirely autonomous in guiding their projects. The present research focuses on one case of these self-guided projects, specifically a two-year-long extracurricular project in the situated context of Politecnico di Milano, where students from different study programmes gather to design and manufacture two racing motorcycles. Students acquire technical knowledge and personal competencies by designing a high-complexity project in such a context. On one side, the project complexity enhances the need to transmit the knowledge and know-how developed by the team in the previous project(s) from edition to edition.

On the other hand, the product's complexity impacts the whole team's work organisation (i.e., workflow, management, communication), a group of around a hundred students. The contextual observation that led to the initial conception of this research has to do with the central role of the designed object in knowledge transfer and team organisation. Students' interaction inside the interdisciplinary and culturally plural workgroup is supported by the material objects representing the motorcycle (e.g., 3d model, mock-up). The observation of this phenomenon led to the development of the research, which focuses on the relationship between the components of the complex object (i.e., the motorcycle) and how they reflect subject-to-subject relationships (i.e., student-to-student relationship). Indeed, such a complex object necessitates the team splitting into workgroups to develop different motorcycle subassemblies. However, the lack of a solid structure for inter-workgroup decision-making creates a barrier to developing a shared understanding of the motorcycle as a whole. Specifically, this organisational shortcoming impacts the design of some components considered not primary and, therefore, not extensively included in the initial phases where requirements and constraints are negotiated between workgroups. The researchers envisioned the possibility of improving such collaborative issues by fostering communication among workgroups using the motorcycle as a channel for communication. To reach this goal, a contextual mapping was developed to make explicit the dependencies between components to construct the net of relationships between workgroups in the team of students. Making components' interconnections explicit means using the same material infrastructure the team uses, hence using an already established communicative channel, i.e., the object, to foster alignment between team members. From the mapping, a meeting protocol was developed and applied to leverage shared and contrasting goals among teams developing related components to achieve a better integrated overall result.

Furthermore, such a protocol has been applied to a specific case study, designing and developing the fairing set for the motorcycle prototype to retrieve data exploiting the material infrastructure regarding designing outcomes. Such a set is considered not primary and shows criticalities regarding dependencies, as it interacts with many different elements at different development stages. One of the researchers participated as a participant observer and designer; this was possible because of a five-year experience as a team member and as head of the Fairings&Aerodynamics department. This hands-on experience allowed the researcher to spot the phenomenon under investigation in the first place but also allowed the opportunity to act to change the team's collaborative practices around the construction of the motorcycle adopting an action research approach. Due to the nature of the team (i.e., self-guided students project), these collaborative practices are primarily based on tacit knowledge. Hence, the research also contributes to formalising the understanding and making explicit how things work in the situated context of the team, where the action research has been later implemented.

Background Knowledge

Theoretical Concepts

We here briefly retrace the theoretical background that helped frame the research; the paragraph deals with the two crucial intertwined phenomena observed in constructing an object and communicating between subjects. It is widely acknowledged that humans have introduced objects in their society till its early stages as tools to interact with the world and other subjects. Subjects may be considered bricoleurs when they exploit their material surroundings to build and evaluate a project (Latour, 1966, p. 9-22). Objects help transmit the project's concept to subjects different from the creator, such as someone working on different aspects of the project or potential users (Carlile, 2002; Carlile 2004). Using a parallel between monkeys and humans, in the symposium *On Interobjectivity* (1996), Latour explains how communication in a human society strongly relies on objects. In monkey society, communication simplicity and straightforwardness are because it occurs exclusively in the present between two subjects, hardly extending through time or pausing and resuming later (ibid). Communication becomes complicated and complex in human societies because humans use objects as a medium to communicate with one actor in the present and simultaneously with actors in different timeframes, from the past to the future. Decisions taken now on the design of an object will have implications on the usability of that object in the future, and human society relies upon infrastructures to work correctly and keep the link between its subjects (ibid). Objects constitute the material infrastructure subjects build to enhance interactions with other subjects: this behaviour is part of the culture created around everyday objects (Attfield, 1999). In her book Wild Things, Attfield (2000) analyses the relationship between users and what she defines as "*wild things*". Wild things can be defined as objects that suffer an evolution through their lifecycle regarding how their users perceive them. Once someone buys the product and it becomes part of the user's life, the object goes from *product* to what Attfield defines as a *wild thing*. This transformation implies that the object gets uncategorised as a mass-produced and widely recognisable product, and it acquires a unique significance for the user that goes beyond its mere practical usefulness (Attfield, 2000). In the present research, three theoretical concepts have been adopted to understand how the *subject-to-subject* (i.e., students-to-students) communication and relationships might be influenced by the *subject-to-object* (i.e., students-to-motorcycle) in the situated context: i) boundary object, ii) prototype and iii) fetish object. These concepts also help analyse the object's role in shaping the culture built by the team and interaction in different stages of development.

Star and Griesemer initially introduced the concept of boundary object (i), which is a sort of arrangement that allows different groups to work together without consensus (Star, 2010). Objects working as boundary objects strongly link with the subject-to-subject relationship, aiming to improve communication between subjects of an interdisciplinary design group. Indeed, boundary objects can support communication between subjects because they are flexible enough to be adaptable and sturdy enough to keep a similar identity across sites (Bender, 2017). So, boundary objects represent intermediary objects between social worlds or disciplines, helping to translate means across the intersected worlds during the design phase. Boundary objects are particularly relevant when considering the innovation process rather than the new product development (NPD) process, as the former is less structured and more creative, while the latter aims to put a product on the market as fast as possible (Rampino, 2022). Hence, in semi-professional realities, boundary objects help to materialise ideas and concepts (Broberg, Andersen, & Sein, 2011), as the design approach could be considered halfway between the innovation and NPD processes. Boundary objects serve groups where participants have only partial knowledge and partial control over interpreting an object or a project (Fominykh, Prasolova-Førland, Divitini, & Petersen, 2015; Anisetty & Young, 2011).

The second crucial role that the object has is the prototype (ii). Previous studies in the field of design showed that new conceptions of prototypes emphasise the theoretical and creative contribution that prototypes make to the research and design processes in addition to the conventional view of what a prototype is (i.e., the first unit of a product to be mass-produced) (Ferraris & Barzilai, 2021). Indeed, prototypes are regarded as means of knowledge production (ibid). Based on Buchenau and Fulton Suri (2000) and Kurvinen, Koskinen and Battarbee (2008), *prototype* (ii) is intended in the present research as a mock-up of a project, a physical representation of a yet-to-be product; they are used to corroborate the design decisions of an object or system. Prototypes are used to communicate aspects of a project independently if this happens in a subject-to-object interaction or if it is intended to be shared with other subjects. Prototypes represent a physical aspect of a project; they are less abstract than boundary objects and less flexible. Their central role is not to function as a common ground for discussion; they represent the outcome of the decision-making developed throughout the brainstorming activity (ibid).

Lastly, fetish object (iii) is the third relevant theoretical concept that helps understand objects' possible role in the situated context. According to Latour (1996), fetish objects become a physical representation of god or idol, more than everyday objects. Therefore, fetish objects are humanised and are granted power by their creator. While grating this power, the creators forget their role as craftsmen or craftswomen. Latour (1996) and Spyers (1998) explain that being *acted upon* provokes, in the subjects (i.e., the creator), *alienation* towards the object and themselves, losing control over the relationship. *Fetish objects* depend strongly on their relationship with the creator and between the creator and other subjects around the item. Such objects are not inanimate tools bought to serve a purpose; they hold control of the *subject-to-object* relationship. This reversal of roles causes the *alienation* mentioned above. Objects work as an interaction framework beyond the design context. Latour (1996) describes the role of things as the interaction infrastructure of society, making stratification of subject interaction along different timeframes possible. For example, the same object works as a boundary object when it acts as a communication medium and as a fetish object as a gathering force for team members.

Contextual Background and Research Proposition

This research focuses on the subject-to-object relationship in the context of a motorsport student team of Politecnico di Milano called Polimi Motorcycle Factory (PMF). In the context analysed, the object helps visualise the issues and promotes brainstorming by building the group's culture around the designed motorcycle (Fig. 1).

Figure 1: The team is divided into five departments subdivided into workgroups. All of them use the motorcycle as a boundary object to promote brainstorming.

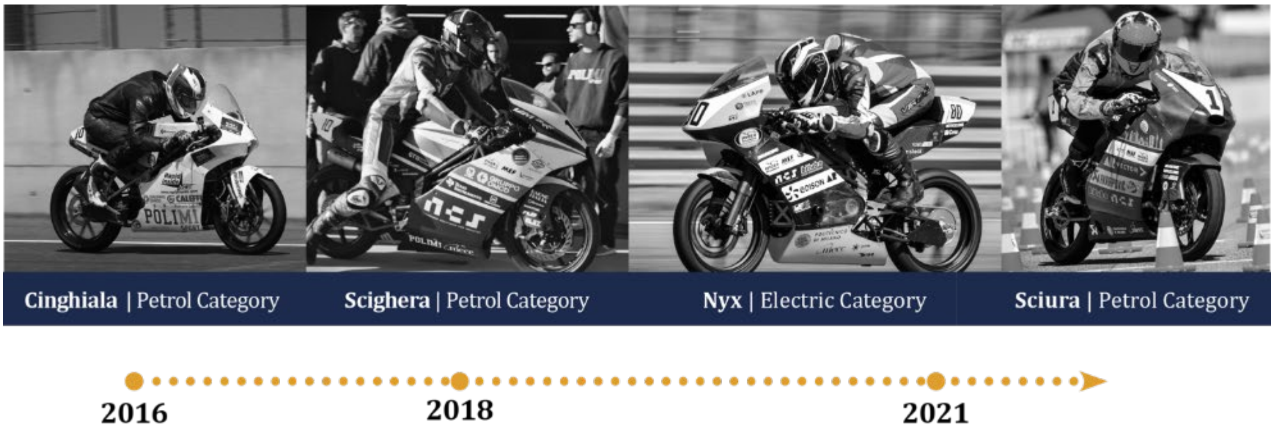


Figure 1: Through participation in the MotoStudent competition, the team has fully developed four prototypes, three for the Petrol category and one for the Electric category. Now is ongoing the development of two new prototypes

The team was founded in 2015, aiming to enrich the university experience with a project to put into practice the knowledge acquired through higher education programmes by designing and manufacturing racing motorcycles. The PMF was born to participate in the MotoStudent International Competition (MEF, 2023), the first student competition dedicated to racing motorcycles. Students teams from different European and international higher education institutions meet every two years in the international track race of Motorland with prototypes designed and built by them. The competition has two categories of racing motorcycles, Petrol and Electric; the PMF has participated in both classes since 2019. Therefore the team raced in three editions, developing four prototypes so far (see Fig.2). In 2016 and 2018, the students developed two motorcycles for the Petrol category, achieving first place in 2018. During the two-and-a-half years till July 2021, the team developed the third petrol prototype and the first electric one. Currently, the team is designing and manufacturing two more prototypes, one petrol and one electric. The PMF is a cross-disciplinary team that includes students from different engineering, design, and architecture study programmes, counting over one hundred students collaborating on a high-complexity project. The project challenges students' learning through the direct experience of a self-guided development of the prototypes in a semi-professional reality. Such a process is coherent with a constructive learning approach, one of the most relevant in contemporary education (Mattioli, 2022).

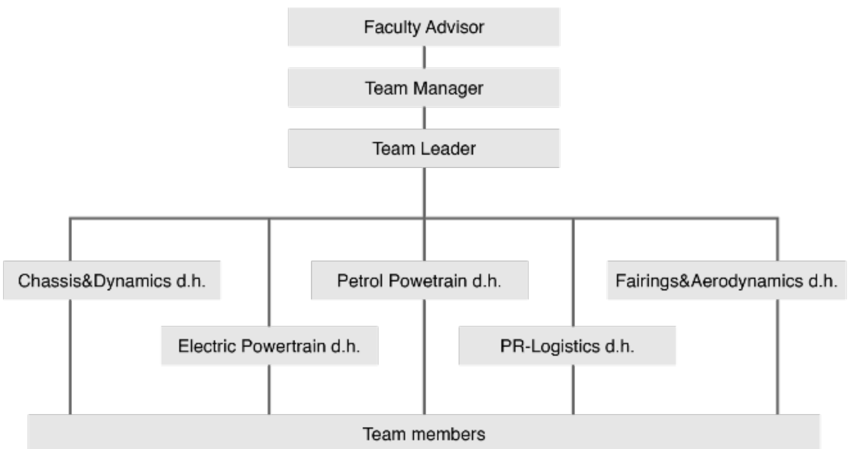


Figure 2: The team's organisation is pyramidal, with team leader and departments heads on top and team members distributed in the departments and divided into workgroups

The team is organised in a pyramidal hierarchy based on a responsibility chain, as shown in (Fig. 3), resembling a professional company structure. The fluid-structure aims to divide and manage the project into tasks and milestones. From top to bottom, the pyramid comprises the team leader, heads of departments and team members divided into collaborative workgroups. Moreover, the whole team has a faculty advisor that facilitates the interaction with the Mechanical Engineering Department, which hosts the team providing a space to work; it is worth mentioning that the faculty advisor has no active role in guiding or supervising the development of the motorcycles. One of the researchers has participated in the project since 2018, having first the role of surface designer and later as the Fairings&Aerodynamics department head. During her participation, the researcher designed and developed four fairing sets. Such experience allowed her to analyse and understand the project approach applied during the evolution of the prototypes. Because of this reason, this research has been applied to the fairing development approach.

Moreover, this experience allowed the researcher to observe the prototype evolution as the material infrastructure guiding subject-to-subject relationships. What has been observed in the context is that the bikes evolve from boundary objects to being perceived as prototypes and finally becoming fetish objects during the design, manufacturing and testing phases (Fig. 4). The bike project starts as an abstract concept in the beginning. Over time the project acquires more materiality, whereas the prototype shape gets set. Communication plays an essential role in achieving materiality. During the design phase, the bike is abstract; it hardly has a well-defined shape. Each workgroup visualises a different representation of the project. During this phase, the object works as a boundary object, representing a communication link between workgroups. Once most components exit the design phase and start the manufacturing and assembly phase, team members perceive the object as a prototype. During this phase, most workgroups share the same project's physical representation.

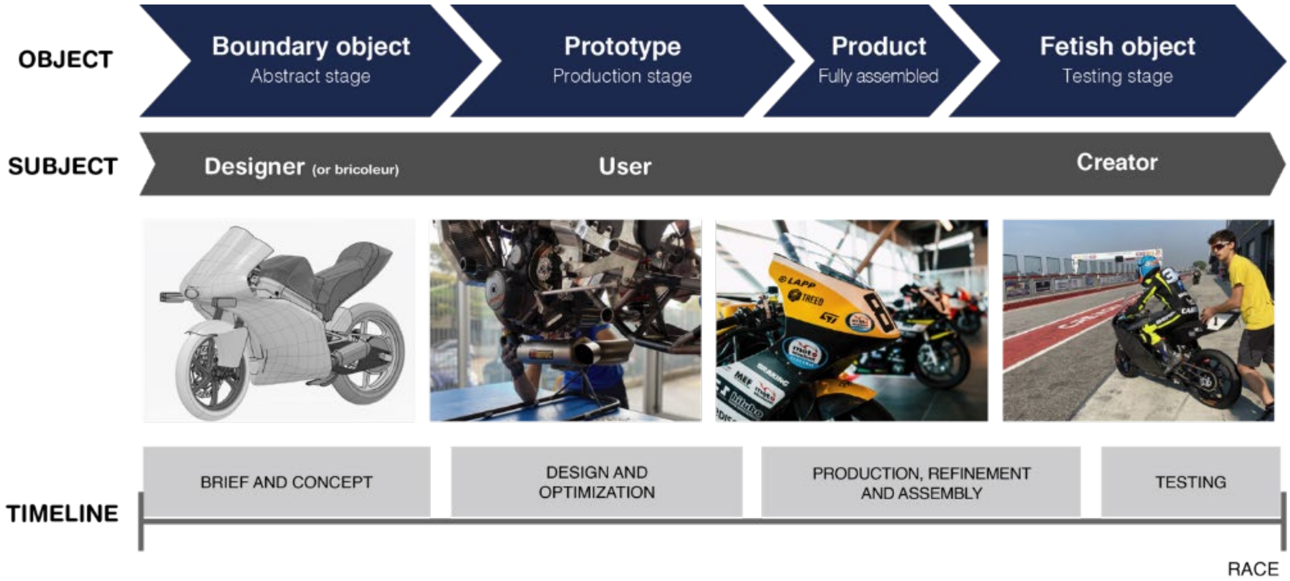


Figure 3 – The motorcycles evolve along the project; in the beginning, while the project is highly abstract, the bikes work as boundary objects, consecutively the project becomes more concrete during the production phase, and the objects transform into prototypes; finally, there is an acknowledgement of aliveness that brings the transformation of the motorcycles in fetish objects.

The more the bike reaches full design maturity, it is recognisable as a product belonging to the widely acknowledged racing motorcycle category. It is worth mentioning that though MotoStudent bikes never really become products because they never reach the market, they stay in the testing category object. Finally, the object becomes a fetish object when the testing phase starts. Team members see the rider as part of the motorcycle and associate the motion with the humanisation of the object. Students acknowledge the object's aliveness through such association, granting it power over themselves.

This observation and framing of the contextual object-to-subject relationship were possible through one of the author's first-hand experiences, as she had the opportunity to participate in the project development, thus following and observing the evolution of three prototypes and the subject-to-object relationship transformation. Concurrently, also the subject goes through an evolution. While the project works as a boundary object, the subjects become designers of such an object; they are not yet considered creators because, during the initial phases, the project is still flexible and under the designer's control. There is a parallelism between the designer figure and the bricoleur described by Latour (1966) because both figures exploit raw material around them as a possible tool to use in a project; objects are under the designer's control. During the manufacturing and assembly phase, the subject is halfway between being a designer and a user because some components get tested. The next shift happens during the testing phase when the object becomes a fetish object, and the subject becomes its creator. The acknowledgement of aliveness (Spyer, 1998) happens the first time the rider drives the motorcycle on a track.

At the end of their lifetime, prototypes are displayed in the hall of the Mechanical Engineering Department, where new members can use them as inspiration: being displayed, they ultimately become fetish objects. Hence, senior members rely on the fetish object power to pass on knowledge. As a result, part of the acquired (tacit) knowledge gets lost during the turnover. Because of this reason, each time a new project starts, the team restarts to rebuild knowledge and project culture almost from scratch. However, most of the overall view gets lost in the turnover, and new members often struggle to develop a broad project understanding. In addition, members' interactions start as an interdepartmental activity and only indirectly with members of different departments through the department heads, provoking members' isolation. This negatively impacts the project because students design each component without considering all other related parts, lowering the overall quality. The guiding research question emerged starting from these contextual observations is: how might we use the object (i.e., the motorcycle in different stages) to leverage collaboration between workgroups? This research addresses the conference theme *"From Abstract to Concreteness"* by analysing the social role of the evolving object inside an interdisciplinary student project to understand the subject-to-subject relationships through the subject-to-object relationships. The goal was to map object-to-object relationships to build a meeting protocol to enlarge brainstorming activities to build a more robust overall perception of the motorcycle as a whole during the early design stages.

Methods and Results

The research follows an action research approach supported by one of the author's first-hand experiences as a participant observer and the in-depth analysis of the petrol prototype designed and developed for the seventh competition edition (i.e., 2023). The action research focused on the work developed by the Fairing&Aerodynamics department and related components developed by other departments. The first step was to set the mapping of the components to analyse object-to-object relationships and then the workflow mapping to understand how the development of each component (with specific regards to those developed by the Fairings&Aerodynamics department) was interrelated with other components.

Components and Workflow Mapping

The fairing set is the aerodynamics part of the project, is not structural, and members perceive it as a covering skin. Because of its size, it depends on many other components, most of which must be developed before the fairing. As a result, the fairing design has little impact on the design phase of the rest of the motorcycle. The researchers first mapped the relationships between components that mirror the subject-to-subject relationships to promote a more cyclic design phase. The following maps helped clarify the link between components developed by different departments.

Figure 4: Cartesian mapping comparing dependency and production strategy

Figure 5 shows a map that compares the x-axis and the dependency and, on the y-axis, the production strategy. The first quadrant includes components considered necessary to test the motorcycle. The second quadrant includes components highly dependent on primary components, and, as in the first quadrant, these components are manufactured in-house. In the third quadrant, there are those components easy to acquire that are not designed. Finally, the fourth quadrant includes essential components that must be set during the design phase. This map aims to highlight the fairing status as a dependent component, whilst the second map shows dependencies between components and helps understand the penalisation in the function of time.

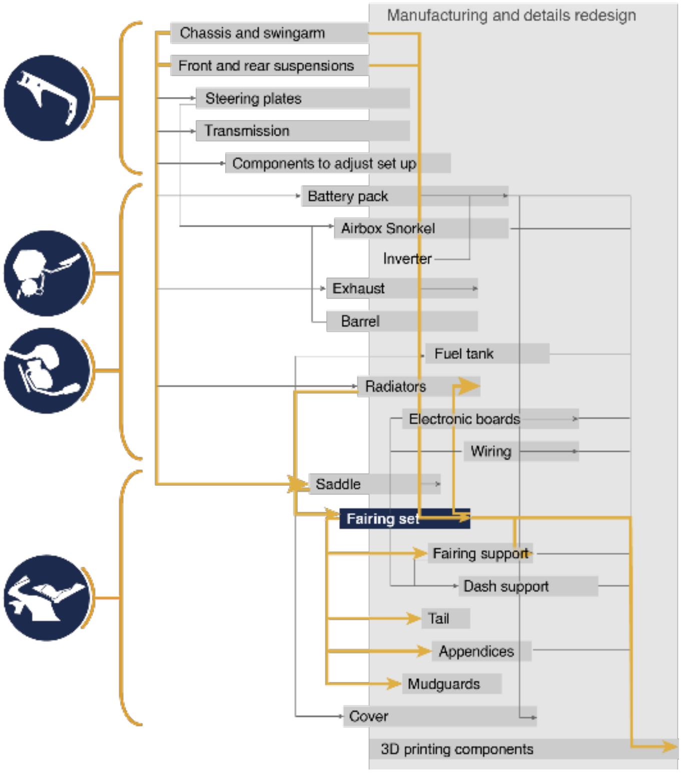


Figure 6: Components' production relationships

Figure 6 shows a Gantt chart that shows the production dependency of components. Such a map help to identify the dependency chain plotted against time, identifying issues related to chains of delay that affect significantly more dependent parts. Some primary components identified in the first map are also considered structural components because, if compromised, the motorcycle is no longer reliable. Such components define the bone structure and the dynamics encumbrances; because of this reason, they are developed first on the timeline. Primary components' criticality and complexity cause delays in the design phase, impacting the available time for the rest of the components. The fairing set depends on the end of the primary components' design phase, which is required for its optimisation approach. Consequently, the fairing is developed when most of the other components have already entered the manufacturing phase, precluding the fairing project from impacting the design of significant components designed outside the Fairings&Aerodynamics department.

The maps helped identify the issues of having an unbalance design process, where the conceptual phase is not developed on the whole motorcycle but on each isolated component. As a result, components considered less critical are treated as extra pieces and are not well integrated. Thanks to one of the researcher's experience, it was possible to trace such unbalance to the communication aspect between workgroups developing different but related components. Researchers have observed that, during the design phase, students developing related components did not share the project perception and work isolated from one another. Due to the stretched social role of the object (i.e., the motorcycle), students rely on its fetish power instead of using material representations as communication and development tools. In other words, each component developed by one department was initially developed without a proper alignment with another department developing related components.

Protocol for collaboration using the object as a boundary object

Since the team lacked structure and a balanced task subdivision, it seemed fair to implement a method that did not require additional time and resources or had to be understood and applied. Consequently, the approach is a protocol for the meetings' organisation with groups of related components. The protocol does not require changing the design method; it should help workgroups receive and transmit information more efficiently, possibly recalling it anytime they need it.

Tab. 1. Description of the protocol criteria for the inter-department meetings.

	Description
Initial alignment	The facilitator clarifies at the beginning of the meeting goals and topics.
Keep it concise	The participants decide a maximum duration for the meeting.
Learn from the past	During the session, the participants analyse both the 2023 design and 2021 prototypes, inviting senior members.
Final alignment	The facilitator recaps all topics.
Follow-up	After the meeting, the facilitator sends a summary of all issues and solutions by email or Telegram channel.

The aim was to increase brainstorming efficiency and trade-off, avoid independent design development of components, and promote a more integrated approach. Furthermore, such change in the project approach should promote competencies growth in a collaborative learning environment, as it reinforces the inter-department negotiation of design constraints and objectives. The concept behind this protocol was to structure brief alignment meetings between interdepartmental groups about specified technical and design topics. These meetings aimed to make explicit information about components design, discuss shared design topics, and achieve shared solutions. The protocol required that the reunions were in person whenever possible and that the criteria presented in Table 1.

Tab. 2. Summary of the five sets of morphological requirements considered while designing the fairing geometry.

Requirements and constraints	*Description*	*Example*
Manufacturing requirements	Geometrical details necessary to permit the production	Draft angles to remove the component from the mould
Material constraints	Morphological characteristics depending on the selected material	Rounds dimensions, surfaces' continuity
MotoStudent race constraints	Maximum and minimum dimensions and encumbrances imposed by the competition regulation	The fairing must not be wider than 600mm and must stay 100mm above the ground with all liquids and without the rider
Extra-departmental requirements	Impositions regarding dynamics and encumbrances of other components developed by different departments	Steering angle, suspensions encumbrances, easy access to perform fastening checks
Inter-departmental requirements	Goals regarding ergonomics and aerodynamics	Rider's visibility, quality of streamlines, surface quality, components' fastening

The protocol was applied to meetings between the workgroups designing the fairing set for both motorcycles and workgroups of other departments developing related components, such as the chassis and the radiator. The main topics were assembly and dynamics constraints, overall vehicle performances, encumbrances requirements and aerodynamics goals. The aim was to set a series of requirements and constraints shared across different workgroups, promoting collaborative brainstorming and knowledge sharing. Then those requirements were divided into five main project goals translated into morphological requirements used to shape the fairing geometry in terms of manufacturing requirements, material constraints, MotoStudent race constraints, extra-departmental requirements, and inter-departmental requirements (see Tab 2).

After the translation, the morphological requirements were applied in the iterative process between design and the computational fluid dynamics (CFD) simulation used to optimise the fairings to improve the vehicle's aerodynamics (see Fig. 7). Thanks to the protocol implementation, enhancing the fairing complexity and integrating with related components was possible. The meetings permitted brainstorming across departments to find common goals regarding components' interface and performance enhancements of one component with the other. Moreover, it allowed members of different departments to learn about the fairing project, enhancing their overview.

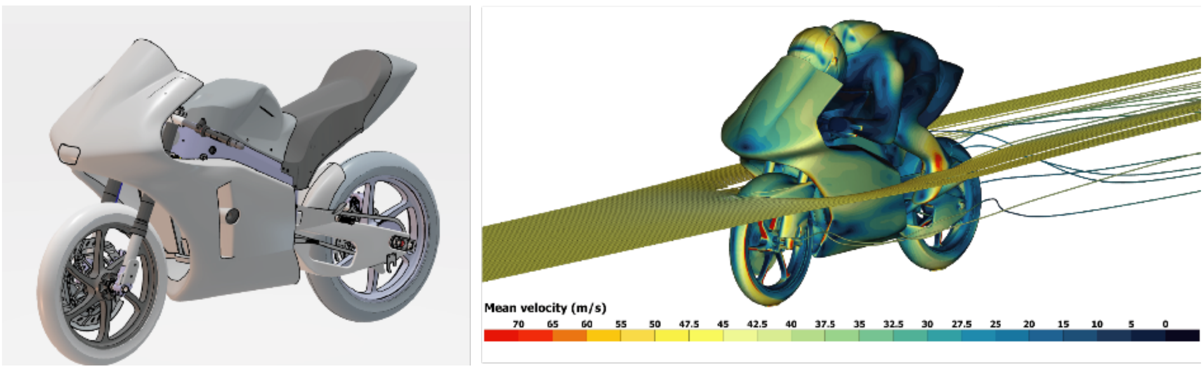


Figure 7: On the left is an image of the CAD model of the motorcycle; on the right is an image from the computational fluid dynamics (CFD) analysis showing streamlines.

Discussion

This research focused on the subject-to-subject and subject-to-object relationships inside the context of the PMF student team. The aim was to understand the prototypes' social impact on the design process. It emerged that such objects are used as infrastructure to establish communication links between team members on different planes and timelines, negatively impacting the current development process and the historical link with previously designed prototypes. To counter it, students use the prototypes and their representations as boundary objects to establish interdisciplinary communication channels as material infrastructure to enhance understanding during brainstorming. The peculiarity of this context is the high-complexity project held by a team of students with no professional guidance. Hence, the questions aimed to clarify the team's collaboration method to leverage the communication quality during brainstorming.

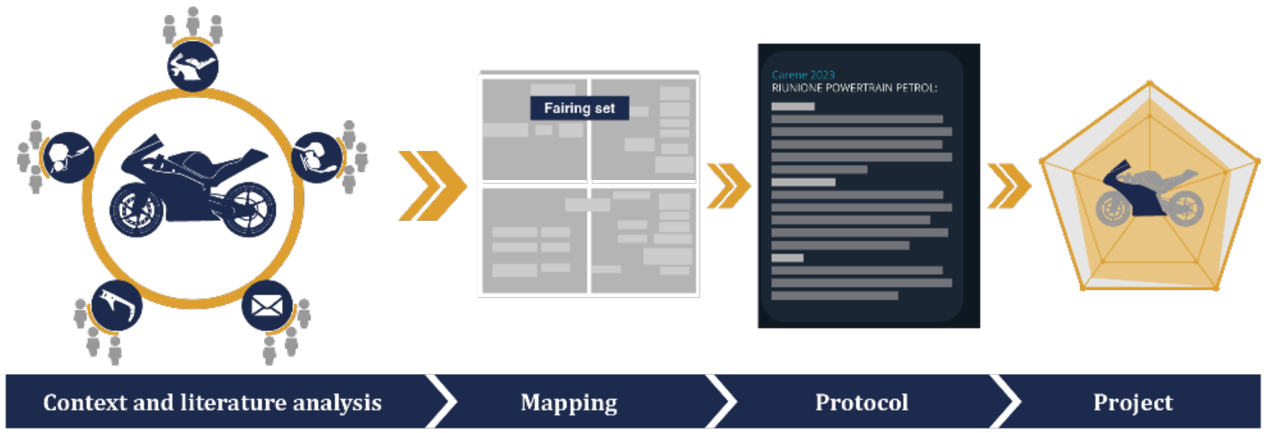


Figure 8: Research process

The authors observed students using bikes as communication channels to promote cross-departmental understanding, maintaining it as a tacit behaviour. The components and workflow mappings were created to display object-to-object relationships as a reflection of the workflow structure. The authors started analysing the method applied to design the motorcycles since the team lacks an official workflow structure. Later they translated the object-to-object relationships into subject-to-subject relationships by tracing the workgroups' project touchpoints. Afterwards, the authors developed and applied a meeting protocol to promote a broad project view and reduce individual component development, aiming to set more shared goals. Later, such a protocol was applied to develop a component that depends on several others. Usually, such a part is penalised during the design phase because of delays from dependent components, impacting its overall quality. The protocol helped leverage workgroup collaboration by creating a contextual path guiding each meeting. It has been noticed that the meeting efficiency depends on the participants' background experience. As a result, if no contextual path and initial goals are set, the meeting outcome does not provide helpful information to the project (see Fig. 8). In conclusion, a few topics have emerged through this research development. Constructive learning contexts inside the university sometimes miss the guiding figure, generating a self-taught process where students develop competencies and project awareness. However, team members miss the process awareness necessary to apply that knowledge strategically to reduce the trial-and-error factor. Moreover, interdisciplinary collaboration is given for granted, which means there is no active process of building personal competencies, so the design process does not exploit such relationships at best.

Subject-to-subject relationships are often built tacitly in this self-directed project through project goals set between related components. Communication channels are strongly dependent on the object's development. The project evolution works as the team infrastructure and not as a tool exploited by a subjects-based project infrastructure. Due to the fetish object's gathering power, different workgroups are put into communication when the object's evolution requires it. Consequently, subjects' connections are dictated by the object-to-object relationships through the evolution of the motorcycles from boundary objects to fetish objects while the students endow in the object the gathering power. Hence, students do not use the object as a tool; instead, they are acted upon by the object.

As a first attempt, the protocol application was limited to developing one component and the workgroups developing related components. To extend its implementation would be necessary to train the management board to open the path to autonomous use, which would be the ultimate goal of the new method. Another limitation regards the project's deadlines. Due to a lack of compatibility, the fairing development did not reach production maturity yet, which would have permitted the retrieval of data about the manufacturing phase and the component testing. Moreover, the research was developed as part of a Master's thesis in Design & Engineering, leading to the implementation of only one action research cycle applied to a small group of subjects related to the development of the fairing set.

This research aimed to improve the explicit knowledge transmitted to the team members to improve their competencies through participation in a high-complexity project. The researchers were able to map the component dependencies to understand the relationships between the subjects and promote awareness about a more integrated design approach. This was possible through analysing and developing a highly penalised component (i.e., the fairing set), promoting interdepartmental collaboration. Future research in the situated context may extend this practice to the design of the whole motorcycle by anticipating collaborative activities aiming to establish a more shared material culture that helps bind the subjects together and reduce project isolation.

References

Anisetty, P., & Young, P. (2011). COLLABORATION PROBLEMS IN CONDUCTING A GROUP. Journal of Computing Sciences in Colleges.

Attfield, J. (1999). Beyond the Pale: Reviewing the Relationship between Material Culture and Design History. Journal of Design History.

Attfield, J. (2000). Wild Things. Great Britain: BLOOMSBURY VISUAL ARTS.

Bender, C. (2017). The Culture Area as Boundary Object. Zeitschrift fur Enthologie.

Broberg, O., Andersen, V., & Sein, R. (2011). Participatory ergonomics in design processes: The role of boundary objects. Applied Ergonomics - Human Factors in Technology and Society.

Buchenau, Marion & Suri, Jane. (2000). Experience Prototyping. Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques.

Carlile, P. R. (2002). A Pragmatic View of Knowledge and Boundaries: Boundary Objects in New Product Development. Organ. Sci.

Carlile, P. R. (2004). Transferring, Translating, and Transforming: An Integrative Framework for Managing Knowledge Across Boundaries. Organ. Sci.

Ferraris S.D., Barzilai G.: The evolving role of prototypes in design research: a discussion on terms and meanings in Di Lucchio, L., Imbesi, L., Giambattista, A., and Malakuczi, V. (eds.) Design Culture(s) Cumulus Conference Proceedings Roma 2021 Volume #2. pp. 1825–1839. Cumulus (2021)

Fominykh, M., Prasolova-Førland, E., Divitini, M., & Petersen, S. A. (2015). Boundary Objects in Collaborative Work and Learning. Research an Innovation Information Systems Frontiers.

Kurvinen, E., Koskinen, I., & Battarbee, K. (2008). Prototyping Social Interaction. Design Issues, 24(3), 46–57.

Latour, B. (1966). The Savage Mind. The science of the concrete. London: Weidenfeld and Nicolson.

Latour, B. (1996). On Interobjectivity. Mind, Culture and Activity, 228-245.

Latour, B. (2021). On the Modern Cult of the Factish Gods. London: Duke University Press.

Mattioli F. (2022). Teaching And Learning Design In Culturally Plural Teams: Collaborative Learning Practices And Experiences In Plural Classes. Doctoral Thesis, Departmento of Design, Politecnico di Milano.

Moto Engineering Fundation (2023). MotoStudent. From MotoStudent: https://www.motostudent.com/

Rampino, L. (2022). EVOLVING PERSPECTIVES IN PRODUCT DESIGN. Milano: Franco Angeli.

Spyer, P. (1998). BORDER FETISHISMS: Material Object in Unstable Spaces. Oxon: Routledge.

Star S.L.: This is not a boundary object: Reflections on the origin of a concept Sci. Technol. Hum. Values, 35, pp. 601–617 (2010)

Azul Amadeo

Master of Science in Design & Engineering, she started her studies in industrial design at Universidad de Buenos Aires, afterwards she continued her learning path at Politecnico di Milano where she graduated. During this period, she participated in an extracurricular self-guided project held in the Dipartimento di Meccanica where students from different courses of design and engineering collaborate to design, develop and test racing motorcycle prototypes. In particular, she contributed as a surface designer; later on, she became head of the Fairing&Aerodynamics department, responsible for the design, optimisation and production of all aerodynamics and ergonomic components.

Francesca Mattioli

PhD, Researcher at the Department of Design at Politecnico di Milano, she is involved in studying design learning and teaching practices through collaborative projects in academic contexts characterised by cultural plurality. Her interests are in developing collaborative skills through design education, particularly in contexts where designer education is conveyed by project development and thus hinged on learning by doing. She is a lecturer in the Master of Science in Design & Engineering, and in the specialising Master in Industrial Design Engineering and Innovation and Industrial Design for Architecture at POLI.design. She collaborates as a researcher in the project "Doctoral Courses System 4 Design" (DoCS4Design), co-funded by the European Union's Erasmus+ program to develop an International Excellence Network among six doctoral programs in design. Since 2023 she has been part of the National Recovery and Resilience Plan (PNRR), in the "Made in Italy Circolare e Sostenibile (MICS)" project.

Proto-flighting in the wild: a creative technologist approach to drone prototyping

Peter Cleveland, Auckland University of Technology
Frances Joseph, Auckland University of Technology

Abstract

The practice of First Person View (FPV) drone flying is not entirely understood. The physics bending agility of the technology and tight coupling of this with a pilot's senses is an emerging field of research into embodied relations and Human Drone Interaction (HDI). The assemblage, integration and tuning of a boutique system of FPV hardware and software that is bound together with open-source firmware in a self-directed mode allows an enormous amount of freedom and application, but also involves tacit knowledge and continuous experimentation that is inextricably bound to processes of prototyping.
The role of a do it yourself (DIY) remote control aviation hobbyist who flies FPV drones is complex and multifunctional. The act of flying these high performance tele-operated robots for recreation is built upon a foundation of specialist craft and technical knowledge across multiple fields that range from materials science to computational systems management. This paper will unpack a creative technologist approach of how a DIY FPV pilot integrates hardware, software and firmware with their drone and generates new experiential knowledge through iterative processes of prototyping across multiple fields. This practice is driven by a desire to perfect a phenomenon known as 'flight feel' that sits outside the normal aims of a staged prototyping scenario and involves a variety of prototyping methods that when combined with modes of sensing and flying in the wild, becomes what could be considered proto-flighting.

Human Drone Interaction; First Person View; Embodiment; Prototyping; Proto-flighting

The development of drone technology has radically impacted warfare, media, research, recreation and industry. It can be understood as a "socio-technical assemblage of the sky and vertical space" (Crampton, 2016, p. 137). Emergent methodological tools combined with new approaches to sensor, power, and control systems of drones offer opportunities to understand the relationship between technology and human. High performance FPV drone technology has quickly evolved into a highly adaptable tool that encompasses elements of making, open-sourced software and technical mastery in which the "human operator is surrounded by the machine, is intimate with the machine, becomes the machine" (Mindell, 2002, p. 63; cited in Garrett & Anderson, 2018, p. 348).

This paper explores a discrete aspect of FPV drone making and tuning processes, and reveals how the relationships between technology, environment and human evolve. It focuses on the embodied experience of fabricating parts and integrating components onto an FPV drone and then the testing of the system by flying at an outdoor location. It interprets how a prototyping 'in the wild' method - an agile development process that enables evaluation and rapid evolution in real life situations (Hutchins, 1996) - plays a key role in achieving FPV flight dynamics. This approach contrasts with prototyping in a Lab or synthetic environment as it foregrounds the spaces between technology, human and environment and offers insights into how the innovation of hardware, software and firmware happens simultaneously, developing new experiential knowledge through processes of doing.

The research presented in this paper sits inside a broader PhD research project that seeks to understand the embodied experience of FPV drones.

Situating FPV drone practice

The process of piloting an FPV drone involves a pilot (human), a drone (technology) and airspace (environment). The role of the pilot in flying an FPV drone is complex. In its simplest technical understanding, the pilot controls or operates the technology or machine while responding to a given environment. Mollica (2020) extends this notion and suggests that the role of an FPV pilot is intricate, immersive, and more than tele-operational in nature. He describes the field of FPV drones as one that encompasses many technical literacies, including specialized systems management, data interpretation, environmental navigation, radio theory, electronics, making, coding, tinkering, flying techniques and practices (2020). He presents a sequential treatment of interrelated topics that build understanding and proficiency in the techne of FPV with the aim of mastering a web of complex technical barriers to "become the machine" (Mollica, 2020, p. 11). This concept extends past a simple technical understanding of a hobby practice and recognizes that the role of an FPV pilot is complex and requires the acquisition of knowledge by doing. Garrett & McCosker suggest that in this modality the drone is not "a simple cyclops eye that flies but rather part of a more-than-human sensorial assemblage" (2017, p.16). This type of close physical association between a human and technology is described by Don Ihde as embodiment (1990). In the context of FPV piloting this suggests that when the pilot masters technical literacy and becomes the machine (Mollica, 2020), the drone and the pilot are one. Eriksson et al., identify this relationship or embodiment as a dialogue that requires a kinaesthetic awareness to achieve inter-corporality between human and drone (2019). This intimacy is also described by Jablonowski as a "carefully and constantly established, attuned, and adjusted relation of mediation between the technological infrastructures of remote control and remote sensing and the embodied sensory perceptions and actions of the human user" (2020, p. 345). This builds a position where the FPV pilot is a do-it-yourself (DIY) prosumer who has a deep relationship with their materials. This extended practice of amateur aviation is supported by a host of social media, web, club and print media resources. This understanding and connectedness allow construction of boutique drone assemblages that best suit the pilot and the environment that they operate in.

In one of Jablonowski's ethnographic interviews the pilot "describes a sensory perception which by far exceeds the objectively transmitted sensor data; he experiences an immediate feeling of synesthetic and kinaesthetic pleasure. The drone becomes a sensory organ of his; due to its mediated coupling with [the] body" (2020, p. 348). In this way, it becomes, what Merleau-Ponty describes as part of his "body schema" (1958). What is not elucidated in these interviews is how the processes of making and integrating the FPV drone operate. These processes are critical to how an FPV drone pilot gauges and evaluates the flight dynamics and ‘flight feel’ of their system. This complex arrangement of understandings and actions could be understood as what Barad defines as ‘intra-action' (1998) where the conditioning between humans and non-humans is one of possibilities. This suggests that a reasonable amount of psychic mobility and out of the box thinking is required to translate bodily and sensory experience into a set of coherent commands and decisions to make pre, real time and post flight adjustments to the FPV drone system that have desired impact. This research paper focuses on understanding the experiential union between pilot and drone by elucidating where the processes of different types of prototyping happens, what some of the key concerns of this activity are and how the experience gained through prototyping affects ‘flight feel’ to gain a better understanding and articulation of these relationships.

Other research has analysed the learning experience of becoming an FPV drone pilot and how that affects connectedness. Tezza et al., surveyed FPV pilots and describe the mechanical relationship of the hand to the remote controller, flying modes and skills gained (Tezza et al., 2021). However, they did not articulate bodily experiences or mental processes. These research findings specifically address how different FPV flight modes change the relationship the pilot has with the craft, they suggest that “future studies could objectively evaluate how each grip mode impacts human-drone interaction” (Tezza et al., 2021, p. 4). This study shows how currently, the subconscious and bodily interface between FPV drone and pilot are not well catalogued or understood. In addition, they note that there is limited research conducted from the first-person pilot perspective or how the making, doing and culture of the hobby operates. The position of the human in the loop as an emerging area of drone research is also highlighted by Herdel et al., (2022) in their scoping review of domains and applications of drone research in Human Computer Interaction (HCI). This paper will directly address this gap in knowledge by revealing how the development of the practice of FPV drone flying is an amalgam of experiential knowledge and prototyping.

The role of prototyping

Design is an integral component of many disciplines including engineering, education, art, architecture, urban planning, business, computer science, and others. Simon suggests that “everyone designs who devises courses of action aimed at changing existing situations into preferred ones” (Simon, 1988, p. 67). This can be understood as meaning that “design” is to improve the world around us. He goes on to frame how examining human created artefacts, involves a departure from the objective observer that has an independent scientific findings model and introduces the science of the artificial, which has human values and actions embedded in it (Simon, 1988). Design researchers have been active in understanding human drone relationships. One recent project explored the proximity that humans will afford drones. Wojciechowska et al., noted that when the drone was within participants personal space, most felt “that the drone wanted to communicate with them” (2019, p. 179). This approach focused on co-location, proximity, and trajectory with a wide range of surveyed participants. This highlights the role of the drone as a functional object that has agency. In this setting it is an item of technology created for shaping and learning about possible futures. Schön suggests that the use of a prototype intrinsically, helps designers learn about design challenges and the world the prototype operates in (Schön, 1983).

An approach to HDI is presented by La Delfa et al., who created a research project called Drone Chi (2020). They present a quasi-chronological pictorial development of the project that had multiple perspectives embedded in its design process (La Delfa et al., 2020). Drones were investigated as a material for designing soma-aesthetic experiences and produced iterative low fidelity prototypes to drive the research development. They found that participants felt the “intimate correspondence” between themselves and the drone, “feel as one with the system” (La Delfa et al., 2020). This sense of union was created by the careful application of soma design principles and prototype development.

Drone presence and interaction is directly addressed by Eriksson et al., in a different setting (2019). They discuss problems and solutions to performance-based drone interaction. They created a choir composed of drones with loudspeakers as a performative choreography for a commissioned opera. In their research they present a methodology where the interactions of the drone and the choreographer are critical to the design phase an aspect of this process is revealed as an evolutionary software prototyping and that it offered "new forms of engagements, such as first-person felt perspectives" (Eriksson et al., 2019, p.1) as key findings that are folded into the final performance of the Opera.

All of these drone human interaction projects used drones as communication objects and had different prototype development as a critical stage in the research. Notably, they were all located in controlled enclosed environments. Hildebrand departs from this model by doing auto-ethnographic research in the wild. She addresses the notion of drone piloting experience by considering flight operations as ‘auratic’, framing it as a playful act that enables “aerial exploration, creative expression, geographical literacy, and imaginative mobilities in ways that suggest expanding conceptualizations of the aerial gaze” (Hildebrand, 2021, p. 20). This points to a heightened relationship between the pilot and the drone where the participant not only feels what the drone sees, but how the drone is performing in the environment. This binding of sensors and human sensing affords new ways of thinking about tele-operation and tele-presence. Jablonowski argues that “drones’ media-technological apparatus allows for a virtual-somatic feeling of presence in spaces where human bodies cannot (or almost cannot) be and move” (2020, p. 347).

A key commonality that links these design research prototyping approaches and theoretical frameworks that situate drone research is the inherent requirement for humans to unionize with the drone system and that it is in more-than a simple tele-operational modality. The possibilities offered by the transdisciplinary, DIY nature of FPV drone practices and the continuous development cycle that the open-source environment, which is inherent in the design and functionality of the technology, positions the FPV drone system and its human pilot as an innovative unified form of prototype that rapidly changes over time and has its own type of agency when located in the wild.

This paper will show how a creative technologist approach to prototyping and evaluation in the field can extend the exploration of new research fields, such as HDI.

A creative technologist approach

This research used a creative technologist approach to engage with drone technology to generate new understandings of the FPV pilots experience and practices. Creative technology is a relatively new field of study (Connor, 2020). The most commonly understood position recognizes the domain as inherently interdisciplinary and draws from multiple fields such as engineering, computer science, design studies and the arts in terms of creative outputs (Mader & Dertien, 2014). Mader and Eggink suggest a creative technologist approach empowers a researcher “to make use of existing technology in novel combinations - in contrast to developing new technology” (2014, p. 1).

The creative technologist approach to this research is grounded in methods such as tinkering, making, hacking and assembling technology to discover possible integrations (Connor and Sosa, 2018). This is accompanied by the forming of an adaptive reflective narrative that allows for the evolution of artifacts and processes to occur. This research investigated the more than human union afforded by FPV drones where "the interaction becomes a dialogue, a negotiation, between the technologies and humans" (Eriksson et al., 2019, p. 3). In this way “the objects, systems and knowledge are constructs that can be challenged and changed as new thoughts, technologies and approaches arise. The process of continuous creation is characterized by ongoing transformations and reconfigurations” (Connor and Sosa, 2018, p. 3). This interdisciplinary approach significantly deviates from traditional design methods around prototyping towards a refined product or service application. It reflects the continuous dialog and interaction that a non-dualistic design process entails to elucidate the relationship that Jablonowski describes as “synesthetic” or “non-human, multi- and extrasensory” (2020, p. 347). This research has used auto-ethnographic methods to record ‘materially discursive’ (Barad, 1998) intra-actions in the wild by recording and mapping flight logs, reflections in and on action, black box data, photography, video and audio. Cycles of action research were interwoven into the practice to drive the tinkering, making, hacking and assemblage components of the research. This hybridized approach as auto-technography, exposed an agile iterative prototyping method as a core component of FPV drone behaviours. It aims to generate new knowledge about the position of the human in the loop in the field of HDI that has been highlighted as being absent by other researchers (Herdel et al., 2022).

Experiencing FPV Fundamentals

This section will describe different types of prototyping that emerged during the research practice of flying FPV drones which enabled the creation of practical knowledge and supported empirical research. The examples involve hardware, software and firmware and were simultaneously developed through iterative cycles of prototyping using the same FPV drone. These activities ranged from materials experimentation and prototyping to open-source software development strategies, such as evolutionary and incremental prototyping development processes.

Location of practice

This research paper focuses on the fabrication and then flying of an FPV drone within a forest environment with the aim of exploring and experiencing it from a new perspective. It also investigates how 'flight feel' is developed. This environment is very complex, with a high occurrence of and extreme proximity to obstacles. For the purposes of this research, the selected flying location was considered a configurement space that was 300 meters x 300 meters x 20 meters in volume. These dimensions were dictated by the radio and video link between the pilot and the drone (refer to figure 1).

Figure 1: (Cleveland, 2022) Flying practice in the forest [photograph]

The practice was carried out daily over a three-month period. A real-world flying location was selected as it would be a challenging extension of practice for the lead author, who has been researching making and flying drones since 2016. It is also in line with New Zealand Civil Aviation Authority regulations (CAA 101 pt.1) that govern the use of drones in the national airspace. The following flight operations were conducted in a privately owned mature conifer forest, in the mode of a 'shielded operation'. Locating the research in a pseudo-laboratory allowed for a real physical environment where the 'doing' component of the practice would not have manmade limits such as volume of space, timetabling and logistics. This approach foregrounded the dynamic nature of the forest environment and atmospheric conditions. This combined with the technology and the human into an amalgam that afforded unified decision making and supported learning about unknowns. This was experienced in multiple ways. Notably, the building of mental flight maps whilst operating in the space became a navigational practice that entailed connecting discovered and possible flight paths together to prototype changes in the technical system and as the practice expanded, increase human generated variables such as risk. Another key benefit to this location was that it allowed the lead researcher aloneness, a scenario that is not always viable in a lab setting and is in line with conducting auto-ethnographic research that had components of audio and video as recorded data.

Hardware

The hardware selection for this project consisted of hobbyist grade componentry. The initial making and configuration of the drone was carried out in an engineering makerspace at Auckland University of Technology. Hacking, tinkering, maintenance and prototyping in the wild was also carried out on location in the forest. The air frame (drone body) selected for this purpose was a kit set consisting of machined carbon fibre plates connected by aluminium stand-offs and fastened together by M3 bolts. It has the key feature of ducts that surround its four propellors. In this instance, the ducts and ancillary parts were 3D printed by the lead author. The novel use case for this drone demanded iterative materials experimentation and rapid prototyping to fabricate ducts that maintained the tolerances required to produce efficient thrust and be robust enough to withstand an amount of contact with flora in the forest environment. The duct iterations started with using a polylactic acid thermoplastic (PLA) material common in rapid prototyping with 3D printers. Multiple adjustments and refinements were made to the stereolithography file (STL) as the prototyping process unfolded to increase the structural integrity of the ducts at the contact points with the frame. After multiple iterations and flight testing of these ducts, a functional accurate prototype was fabricated out of nylon using selective laser sintering (SLS), an industrial 3D printing process (refer to figure 2).

Figure 2: (Cleveland, 2022) SLS 3-D printed componentry [photograph]

In tandem with this iterative prototyping was the selection of the type and sizing of the propellors, which had to be cut down to very specific tolerances, to suit the critical dimensions of the ducts. The propellor selection moved from high pitch tri blades to low pitched octo blades. The shape and mechanical properties of the blades had a big impact on the flight dynamics of the drone. A jig was fabricated and fitted to a rotary tool that allowed replication and precision when cutting the blades to length and many iterations and trials of blades with different properties such as aerofoil, chord and pitch distribution were prototyped. It was not possible to simply generate data from a static thrust calculator to simulate and predict the duct, blade and motor combination to forecast performance. The amputation of the end of the blades and duct configuration disrupted any attempt at using a software-based calculator and produced highly variable, unusable results. Evaluation and decisions about the effectiveness of each blade type was driven by what soma designers describe as “first-person felt perspectives” (Eriksson et al., 2019). Achieving maximum performance from the ducts, propellors and motor combination enabled the drone to be more efficient with each iteration. However, the results achieved were such that during the practice a new soft material, Thermoplastic Polyurethane (TPU), that was more tolerant to contact with flora at velocity was 3D printed and introduced. This became necessary as the kinaesthetic awareness of the pilot and risk taking with the drone in the environment increased. This physical prototyping and holistic negotiations with the drone and the environment produced a ‘flight feel’ that was bright, nimble and robust. The role of iterative prototyping and iterative material experimentation in tandem during this process was crucial in developing the drone (refer to figure 3).

Figure 3: (Cleveland, 2022) TPU 3-D printed componentry fitted on the drone with cut down propellors [photograph]

Software

Software is a continuous site of development for FPV pilots. The open-source network of developers and supporting social media resources are constantly bringing to production software hacks and applications that can be integrated into the FPV drone system. Releases of this boutique software are often deposited on the open source Github platform and supported by a temporary community that evolves around the project. Real-time feedback from the developers and community is then available for problem-solving and testing in an agile development mode. An example of this was the hacking of the digital DJI air unit and FPV goggles, used by the lead researcher on this project, to provide an external stream of the digital video feed coming from the drone onto a secondary platform. The code was first made available to the FPV drone community as a linux image hosted on a Raspberry Pi and involved iterative cycles of trial and error to install and configure before becoming stable enough to use. This evolutionary software prototyping process in its initial stages was functional but proved cumbersome to use in the field due to the amount of apparatus required to support it. A refinement of this application became available from the open-source developers in the form of a software developers' kit (SDK app) that could be run on an android device. This evolutionary prototyping approach from the open-source developers resolved the issue of portability and allowed this research to stream and record video off board from the DJI googles and air unit platform, in real time. An unexpected advantage of this was that playback from flights was available in the wild which allowed for reflection in and on action and highlighted the performance of the drone whilst prototyping the various duct and propellor configurations. This was displayed on a flat screen that could be analysed and played back at different speeds. What emerged from this new ability was a sense of how the different ducts affected the flight dynamics of the drone with regard to slowing it down. The form factor and materials of the ducts had a very big impact on the performance of the drone as the ducts acted as an air brake which was in many respects more useful for controlling the drone in the forest environment than optimising thrust and power which was the initial aim of the process. The amalgamation of materials prototyping, and open-source software prototyping - which can be described as an incremental prototyping process - allowed the researcher new opportunities to explore space in a more than tele-operation mode guided by “first-person felt perspectives “(La Delfa et al., 2020).

Firmware

Interlaced with all parts of the drone system is the firmware that runs the flight controller. Firmware can generally be considered embedded code that provides basic instructions that sets the behaviours of the hardware and allows communication with other software running on a device.

This research used the open-source Betaflight firmware hosted on a specialised hobbyist flight controller board. This firmware comes with a host of companion applications and a very powerful configurator that allows adjustment of every variable in the system. A fundamental feature of the Betaflight soft and firmware architecture is a focus on flight dynamics and performance which is managed through a Graphical User Interface (GUI) called Betaflight Configurator. This interface, which is achieved via a USB connection to the flight controller board, allows complete control and tuning of the low order flight controller settings as well as management of the peripheral devices connected to it. This tool is available on multiple platforms (such as a laptop) and can be used on location in the wild.

In essence, the GUI is how an FPV pilot talks with their drone and is a capacity that Mollica suggests is a vital form of technical mastery (2020). This software tool, we suggest, allows what Barad identifies as “material discursiveness” (1998) by giving the FPV pilot an ability to drill down into the exact behaviours of both the human and technology sculpted for a particular environment. This is achieved by the GUI affording a granular level of detail and control of any part of the FPV drone system without concern for any other part of it. Reflection on the performance of the drone is also available through a process of black box recording and review and produces a flow of data that can be analysed using a companion open-source application, Betaflight Black box log viewer. This is an interactive viewer which allows the pilot to closely analyse actions and responses of the system to any given input, post flight. This can then be acted upon by changing firmware settings or addressing any highlighted hardware issues. This capability is a major departure from closed source consumer drone systems that limit access to individual settings by providing a curated user experience. This data stream is also an important component in building maps of experience (refer to figure 4), as it can be used to visualise data from a flight when rendered with video footage captured from the drone. This can then be combined with other data streams such as global positioning system (GPS) and auto-ethnographic footage of the pilot to present a new perspective of the experience of flying an FPV drone in the forest where the technology, the human and the environment have agency.

Figure 4: (Cleveland, 2022) Map of experience [screenshot]

From Prototyping to Proto-flighting

The attunement modality between the technology, human and environment is in practice a step change model that begins with technical process and techne, as craft or technique, being paramount.

This standard FPV pilot behaviour/practice began with flashing the latest version of the Betaflight firmware onto the flight controller board and completing a digital and physical integration of the parts of the drone system. This was validated by doing short test flights. The next steps involved computational considerations, such as the rate that the flight controller achieves a desired input from the handheld remote controller (RC) highlighted by (Tezza et al., 2021). Then attention to the tuning of more complex relationships such as radio link data packet management and filtering. Each of these integral intra-actions built an objective understanding of the FPV drone assemblage and was a starting point for a continuum of conversation between the technology, the human and the environment centred around the firmware. As the system stabilised and became suitably predictable, the kinaesthetic experience changed from one of newness and uncertainty to one of sympathy and resonance. The embodied perceptions of flight transformed into a simultaneous experience of rhythmic velocity and confidence in taking risk, uninhibited by the minutiae of command-and-control and was sensed as a flow of colour and space.

These glimpses of the possibilities of flying in the environment were due to tactical deconfliction of the drone system and its pilot and an emerging comfort with the environment. This type of sensing was initially for short bursts of time and indicated that a new phase of inter-corporal engagement was emerging. This was a product of human and technology seamlessly coming into union in an environment that, over time, became more accommodating. An example of this was the experience of being lost whilst flying in the forest and having to continue flying whilst nervously considering battery consumption. A sudden shift into listening intently for the drone and recognition of a specific pool of light around a fallen tree re-established positionality and relationship between the drone and the pilot. This afforded a successful physical reunion between the two but also created synesthetic experiences such as uncontrollable knee shaking and butterflies in the stomach. During the initial stages of this research these types of experiences in the environment would often end in crashing and the pilot having to walk around the forest environment to recover the drone. This also fostered a new intimacy with the environment as the maps of experience extended to include different layers such as canopy, sub canopy, scrub, herbaceous and aquatic layers of the forest environment.

At the end of each test flight consideration of moments in time during the flight that inhibited or accelerated the experience were translated into an adjustment or reconfiguration of the system via the GUI until a harmonised arrangement was reached. The researcher also recorded the feel of the flight as notes in the form of flight logs and reflections. These reflections on action also took in how other inhabitants of the forest negotiated the complex environment and commented on how successful emulating them with the FPV drone was. An example of this is how the New Zealand Fantail, a small insectivorous native bird that is a constant companion in the forest, darts about in the sub canopy, with rapid direction and elevation changes. This was a very different flight path strategy that resulted in many contacts with the flora and a focus on fighting crashes when they were happening so as to fly through the incident rather than give up and disarm the drone when entanglements or contact happened. By continuous adjustment of the system and adaptive practice as a pilot, flight pathways which were an exciting procession of near misses emerged. This opened the range of possible flight operations up to include small waterways and near to ground shrub terrain and allowed a type of diving and swooping from the canopy into ground level biota. This development produced a high energy feeling of free-flowing flight in the forest and gave new insights into how the experience of FPV fundamentals can be evolved into new maps of experience to suit what would normally be considered a hostile aviation environment.

The experience of prototyping in the wild highlighted an inflection point that emerged during test flying the FPV drone. This was when technical concerns diminished and an all-encompassing involvement in the moment of flight was amplified. The new modality could be considered proto-flighting where optimising a prototype transforms into an optimal experience. This objective unpacking of what Jablonowski terms as ‘more than tele-operational' (2020) is anchored in the perceived feltness of the changes made in the flight dynamics of the FPV drone, new spatial awareness and making things happen. This highlights how a creative technologist approach using different prototyping strategies and auto-ethnographic practices can combine to create new experiential knowledge in the FPV drone space.

Conclusion

This paper unpacks how a creative technologist approach, weaving multiple prototyping strategies together, enables the creation of new understandings and supports auto-ethnographic research in the area of HDI. The foregrounding of the lived experiences of how an FPV pilot develops with the technology in the wild is one that involves multiple forms of prototyping including rapid, iterative, incremental and evolutionary prototyping strategies. The uncovering of air braking as an important flight dynamic in a forest environment was made possible by amalgamating experiential knowledge and different types of prototyping. This was carried out across multiple domains simultaneously, that then transformed into the felt experience and method of proto-flighting. The building of auto-ethnographically recorded and reflected upon data layers combined with embedded technological data tracking introduces opportunities for new understandings and experiential knowledge in the form of maps of experience. This approach of layering captured video and audio data, black box logs, flight logs and reflections can give insights into the dynamics and embodied experience of flying FPV drones. This research begins to address a gap in knowledge about the 'human in loop' highlighted by Herdel et al., (2022) by exploring and articulating practices and behaviours of an FPV pilot in a real-world scenario that can be understood as proto-flighting in the wild.

References

Barad, K. (1998). Getting real: technoscientific practices and the materialization of reality. differences: A Journal of Feminist Cultural Studies, 10(2), 87+. https://link.gale.com/apps/doc/A54772266/AONE?u=anon~f4badcf0&sid=googleScholar&xid=6c220d36

Connor, A. M. (2020). Creative Technologies: A Retrospective. International Journal of Innovation, 13(6), 23. http://hdl.handle.net/10292/13417

Connor, A. M., & Sosa, R. (2018). The A-Z of Creative Technologies. EAI Endorsed Transactions on Creative Technologies, 5(15), 154460. https://doi.org/10.4108/eai.10-4-2018.154460

Crampton, J. W. (2016). Assemblage of the vertical: commercial drones and algorithmic life. Geographica Helvetica, 71(2), 137-146. https://doi.org/10.5194/gh-71-137-2016

Eriksson, S., Unander-Scharin, Å., Trichon, V., Unander-Scharin, C., Kjellström, H., & Höök, K. (2019). Dancing with drones. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1-12. https://doi.org/10.1145/3290605.3300847

Garrett, B., & McCosker, A. (2017). Non-human Sensing: New Methodologies for the Drone Assemblage. In E. G. Cruz, S. Sumartojo, & S. Pink (Eds.), Refiguring techniques in digital visual research (pp. 13-23). Springer. https://link.springer.com/chapter/10.1007/978-3-319-61222-5_2

Garrett, B., & McCosker, A. (2017). Non-human Sensing: New Methodologies for the Drone Assemblage. In E. G. Cruz, S. Sumartojo, & S. Pink (Eds.), Refiguring techniques in digital *visual research (pp. 13-23). Springer.* https://link.springer.com/chapter/10.1007/978-3-319-61222-5_2

Herdel, V., Yamin, L. J., & Cauchard, J. R. (2022). Above and Beyond: A Scoping Review of Domains and Applications for Human-Drone Interaction. CHI Conference on Human Factors in Computing Systems, 1–22. https://doi.org/10.1145/3491102.3501881

Hildebrand, J. (2017). Situating hobby drone practices. Digital Culture & Society, 3(2), 207-218. https://doi.org/10.14361/dcs-2017-0212

Hildebrand, J. M. (2021). Aerial Play: Drone Medium, Mobility, Communication, and Culture. Springer Singapore. https://doi.org/10.1007/978-981-16-2195-6

Hutchins, E. (1996). Cognition in the wild. MIT Press.

Ihde, D. (1990). Technology and the Lifeworld: From garden to earth. Philosophy of Technology.

Jablonowski, M. (2020). Beyond drone vision: The embodied telepresence of first-person-view drone flight. The Senses and Society, 15(3), 344-358. https://doi.org/10.1080/17458927.2020.1814571

La Delfa, J., Baytas, M. A., Patibanda, R., Ngari, H., Khot, R. A., & Mueller, F. 'Floyd'. (2020). Drone Chi: Somaesthetic Human-Drone Interaction. Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, 1–13. https://doi.org/10.1145/3313831.3376786

Mader, A., & Dertien, E. (2014). HOW TO EDUCATE FOR CREATIVITY IN CREATIVE TECHNOLOGY? DS 78: Proceedings of the 16th International Conference on Engineering and Product Design Education (E&PDE14), Design Education and Human Technology Relations, University of Twente, The Netherlands, 04-05.09.2014, 04, 6. https://www.designsociety.org/publication/35941/How+to+Educate+for+Creativity+in+Creative+Technology%3F

Mader, A., & Eggink, W. (2014). A DESIGN PROCESS FOR CREATIVE TECHNOLOGY. 6. International Conference on Engineering and Product Design Education 4 & 5 September 2014, University of Twente, The Netherlands https://www.researchgate.net/publication/265755092_A_DESIGN_PROCESS_FOR_CREATIVE_TECHNOLOGY

Merleau-Ponty. (1958). Phenomenology of perception. Routledge.

Mollica, C. M. (2020). FPV flight dynamics: Mastering Acro mode on high-performance drones. Vespula Ventures LLC.

Schön, D.A. (1983). The Reflective Practitioner: How Professionals Think in Action. Basic Books, New York, NY. 62.

Simon, H. (1988). The Science of Design: Creating the Artificial. Design Issues, 4(Designing the Immaterial Society), 67–82. https://www.jstor.org/stable/1511391

Tezza, D., Laesker, D., & Andujar, M. (2021). The Learning Experience of Becoming a FPV Drone Pilot. Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction, 239–241. https://doi.org/10.1145/3434074.3447167

Wojciechowska, A., Frey, J., Sass, S., Shafir, R., & Cauchard, J. R. (2019). Collocated Human-Drone Interaction: Methodology and Approach Strategy. 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), 172–181. https://doi.org/10.1109/HRI.2019.8673127

Peter Cleveland

Peter Cleveland is a PhD candidate at Huri Te Ao/The School of Future Environments at Auckland University of Technology, New Zealand. His research is engaged with processes of making and embodied experience with a focus on Human Drone interaction. He is an avid enthusiast of technology and its implications on our present and future world.

Frances Joseph

Frances Joseph is Professor of Material Futures in Huri Te Ao/The School of Future Environments at Auckland University of Technology, New Zealand. Her research is concerned with materiality and embodiment, and includes areas of intra-active systems analysis, material ecologies and making-with. Frances is the primary supervisor of Peter Cleveland's Doctoral research project and is secondary author of this paper.

DIY Bus: Exploring Boundary Objects in Participatory Design Research

Dhriti Dhaundiyal, School of Design, Doon University, India
Nishant Sharma, IDC School of Design, IIT Bombay, India

Abstract

Inequity in access to public transport is created when infrastructure and services are created for the default 'generic user'. Policy formulation for large populations is driven by statistical analysis and data-driven models that often do not account for marginalized user groups, like women. A participatory approach to policy formulation can give a voice to the tacit, unrepresented needs of these groups. This research aims to evolve a comprehensive, context-sensitive participatory design research toolkit for public transport that helps in requirement capture of user aspirations and tacit knowledge. Building prototypes together helps in bringing out experiential knowledge of the participants. The prototype building toolkit serves as a boundary object that helps in tangible expression and facilitates conversations. The participatory workshops helped generate new insights into the women participants' lived experiences, and served to give a tangible form to the abstract concepts in their minds. The group discussions brought many tacit needs to fore, giving voice to their unarticulated thoughts. The built prototypes embodied the participants' aspirations for better, safer public buses.

Public Transport, Boundary Objects, Participatory Toolkit

Mobility is an important factor in women's empowerment in the modern world. Increased employment among women in India, in addition to their domestic tasks, has greatly amplified their need for mobility. However, the few options available have negatively affected their ability to work and choice of work (Pas, 1984). The World Bank Report on Gender and Transport (Bamberger et al., 1999) first ventured to say that transport can boost women's productivity and promote social equity, acknowledging the lack of access and safety. In developing countries, more women have no mode of transport available at all and generally walk, more women depend on public transport, fewer women have access to motorized transport, and even fewer of them are likely to use bridging transport like bicycles (Peters, 2015). These disparities have resulted in a sort of gendered IM-mobility for females, resulting in what has been termed as 'transit captivity' in critical literature where geographies and reach of a significant section of society have been limited by their lack of ability to move in a safe, accessible and economical way.

Generative design techniques can help unearth the underlying reasons behind this transit poverty. We posit that participatory research can be used with groups of diverse participants from varying backgrounds, bridged by boundary objects. The main challenge is converting tacit knowledge (described as valuable and highly subjective insights and intuitions that are difficult to capture and share) to explicit expression (defined as objective and transferable). Boundary objects are tangible artefacts that serve to facilitate communication and coordination across diverse individuals or teams. They help create a common ground to exchange or generate knowledge between different domains, cultures, stakeholders etc. With this aim in mind, we created a customized toolkit of a

DIY bus model, where participants build their ideal bus together, while voicing their concerns and reasons. This paper presents exploratory findings from three workshops we conducted with the toolkit. We begin the paper by presenting the background literature that justifies our selection of prototyping with boundary objects as a research methodology. Further, we detail our workshop protocol and present findings from the workshops. We then discuss the patterns observed across the three groups of participants and the prominent themes observed.

Background

Women & Public Transport

Transport planners, geographers, economists and policymakers have studied the vastly different travel needs and travel patterns of men and women globally. It has been found that mobilities can enable, disable and modify gendered practices in society (Hamilton & Jenkins, 2000; Turner & Grieco, 2000). It is seen that women generally make poorly resourced, highly complex, multiple-purpose trips (trip chaining), while men tend to make single-purpose trips at a higher cost and generally use the personal mode of transport over shared or public transport, attributed to the gender-differentiated roles in families, leading to distinct differences in purpose, distance, mode, time of travel, time travelled, destinations etc. (Peters, 2015). These differences in mobility and travel patterns can be accounted for by differential access by gender to economic, social, and time resources.

Public transport in India is currently designed for the fit and able, leaving out large groups of physically, socially or economically disadvantaged people. Existing policy is based on large-scale quantitative data. However, there is a scarcity of qualitative studies that look at the tacit, unvoiced reasons for issues faced by women using public transport. This has led to generic solutions, often a simple copy of established Western paradigms. A deeper, richer, and more participative study is needed to correctly identify problems and possible design interventions in local trains. Understanding the unsaid, tacit needs can help convert more women commuters to public transport, and help retain them in the long term. To explore latent needs of women in public transport, generative tools of participatory design can be used to explore what women know, feel and dream.

Participatory Design for User Insights

Participatory design methodology includes methods to co-create, co-operate, and co-design solutions with real users or participants. It brings the design researcher and the end user together as co-creators and collaborators. The design researcher brings to the fore their expertise in forging designs as prompts, and the participants bring their expertise from lived experience to the table. Users may not necessarily have the expertise to create detailed concepts or a technical understanding of manufacturing requirements, but they are the greatest experts of knowing their own experiences. Users have 'memories' formed by their use of the product or service in the past, and 'dreams' based on their hopes and aspirations from the product or service. A well-designed participatory toolkit should be able to elicit those experiences and help capture the participants' memories and dreams in the present moment (Sanders et al., 2014).

Participant knowledge varies from surface level to deep level. One of the challenges of user research is to make people say what they really want rather than what they expect the researcher to hear. What people 'say' or 'think' is often superficial in nature. This can be found out by simpler and more direct techniques like interviews and is termed 'explicit' knowledge. Participants' actions, or what they 'do', or how they 'use' a product or service goes a step deeper below the surface. They can be revealed through detailed and systematic observation studies. This is termed 'observable' or 'tacit' knowledge. The deepest level of user insights involve what they 'know', how they 'feel' and what their 'dreams' are. This kind of 'latent' knowledge can be learned only through generative methods (Stappers et al., 2014).

Prototypes in Generative Research

Artefact based approaches in participatory design leverage prototyping as a way to iteratively create design solutions. The use of analog tools is popular in understanding user requirements in participatory research (Borum, Petersson, & Frimodt-Møller, 2014). Recently, there have been many studies with customized tools, designed specifically for research in specialized areas, like Dan Lockton's Design with Intent Toolkit (Lockton, 2017) and the LEGO® SERIOUS PLAY® kits (LEGO Group, 2010). The LEGO® SERIOUS PLAY® (2010) method was developed as a 'facilitated thinking, communication and problem-solving technique' to spur active participation and gain deeper insights from enhanced creative thinking, expression and communication. Many recent studies have used customized toolkits for research with successful outcomes (Liu et al., 2022; Baldassare et al., 2020; Peters et al., 2021).

Prototyping in artefact-based interventions can be applied in workshops with diverse participants, across gender, age, national and linguistic background, professional experience and seniority. They have been seen to overcome some hierarchies and hegemonies, which possibly exist in such social contexts, thus facilitating parity in the voice of all participants. Integrating Artefact-based interventions into discursive research practices amongst stakeholders has been found to create high engagement, generation of a broad spectrum of ideas, and a shared vision of research (McCusker, 2019).

Prototypes as Boundary Objects

Artefacts like prototypes can serve as boundary objects in research. Boundary objects are socio-technical constructs that may be semantic, syntactic, pragmatic or metaphoric, depending on role and context. They were first conceptualized by Star & Griesemer (1989) while working on creating common ground in diverse research teams. They have a distinct identity, yet are flexible and accommodate varying viewpoints. The boundary in 'boundary objects' refers to the shared space between entities which is flexible and open to different interpretations (Star, 2010). Star & Griesemer (1989) identified four categories of boundary objects, repositories, ideal types, coincident boundaries and standardized forms. Cross-disciplinary research requires cooperation across teams with diverse backgrounds and domains. Cross-disciplinary collaborations that combine design approaches and scientific knowledge have been found to lack common definitions for interactions, methods, processes etc. (Välk et al., 2019; Tsekleves et al., 2019; Schindler, 2015; Dunne and Raby, 2013).

Boundary objects provide a common ground that helps maintain research integrity while acting as a research probe to elicit responses and reactions from a varied group. Bowker and Star (1999) further expanded on it with reference to disparate "communities of practice" where each has a different classification system or social world that has naturalized objects over time. Boundary objects lie in the peripheral, shared worlds of these communities, not fully naturalized by any community but still, are understood by them.

In organizations, boundary objects serve to create bridges between individual functions and repositories to propagate knowledge sharing and transfer across different verticals (Kanwal et. al., 2019). Boundary objects have also been adopted extensively in computer supported cooperative work and information science. A boundary object can take the form of a diagram, a metaphor, an instruction booklet, a repository, a coding system, a prototype, a story, a digital prompt, or even a conceptual artefact, to name just a few possibilities. Boundary objects have been found to promote communication in groups working with software systems and decision-making (Fong et al., 2007; Huang & Huang, 2009; 2013). They have also been found useful in enhancing communication in community research and practice (Impedovo & Manuti, 2016; Huvila et al., 2017).

Studies across different participatory studies with marginalized populations have found that boundary objects made to provoke an impulse for change can help trigger people to social change (Groot & Abma, 2021; Melo & Bishop, 2020; Hsiao et al., 2012; Akkerman & Bakker, 2011). They elicit an emotional response through recall or association maybe and bring to the fore tacit, unarticulated thoughts. In fact, provocative objects may create dialog and spur action for change (Groot & Abma, 2021). Boundary objects are not universally useful or applicable of course. Oswick (2009) found that misappropriation of boundary objects lead to barricades in the research process, reinforcing existing structural flaws and problematic hierarchies.

Methodology

The goal of this research is to explore the use of prototyping in participatory research to generate qualitative insights into how women use buses, in order to identify tacit needs of women in India using public transport. Our hypothesis is that an artefact based participatory toolkit can help us capture tacit requirements of women.

Sampling

The first workshop was treated as a pilot, where women participants were chosen based on convenience sampling in the host institution of the researchers. Participants were limited to design students. The next two workshops were conducted as part of an international participatory design conference held in India, in a different institution located in a different city. Participants could sign up for the workshop voluntarily. Participants were women who were design and architecture students and faculty, city planning professionals, social scientists etc. We secured institutional ethics approval for research with human subjects, and consent was obtained before the workshop from all participants for video and audio recordings of the session.

Pre- Workshop Sensitization

The sensitization questionnaire was planned to 'warm up' participants and act as a gentle trigger for their previous experiences in traveling by public buses. The participants are asked to spend 10-15 minutes answering questions at leisure. Questions like 'Why do you take the bus?', 'When do you take the bus?' are meant to make them reflect on their travel decisions. There are further prompts to take the participants back to their bus ride, like time spent on various activities 'While you wait/While boarding/While riding/While deboarding'. There were also some probes to help the participants reflect on issues that have been flagged in previous workshops (Dhaundiyal & Sharma, 2022b). The participants were also given some scenarios like 'What do you do when: You bought 5 kg of potatoes; Someone keeps pushing into you; You see someone suspicious?; It's getting late at night. You are alone on the bus, etc.

Workshop Protocol

After the sensitization session, participants were invited to use the toolkit to create a bus service they see as ideal. The artefacts of the toolkit were kept neatly in the centre of the workspace with no attempt at any kind of segregation into categories. The researchers observed the interactions between the participants and the toolkits, and also the interactions of the participants with the other participants. The participants were given 60-90 minutes for the participatory session. No verbal prompts or probes were given. All prompts were in the form of the artefacts in the toolkit only. The entire session was recorded on video for later analysis. Researchers noted down their observations during the workshop. The cameras were set up at optimal vantage points, to capture maximum details of the proceedings without intruding on the proceedings of the participatory session.The researchers played the role of facilitator in leading the session but instructions were given in the form of guidance rather than dictats. Facilitators made the participants feel that every opinion, experience is useful and would be respected.

For analysis, the researchers took extensive notes and made observations during the three workshops. Post the workshops, we analyzed the recordings and created annotated timelines, noting down some quotes that highlighted themes. We first created timelines for each workshop, and then studied them in tandem to study different courses the sessions took. We then identified recurring themes and patterns.

Development of the Toolkit

Based on our requirements and results from earlier workshops (Dhaundiyal & Sharma, 2022a), we selected a hybrid form for our toolkit, a DIY bus-building kit. Some bus elements were in abstract form, and some specific object and human triggers were built in concrete, recognizable forms. We selected a scaled-down, abstracted form of the bus so that people could relate to and recall the space inside a bus. Visualization of the actual space inside the bus is important, so a close-to-reality toolkit will help participants to acutely recall the space and their experience in it. We kept the toolkit modular to ensure maximum flexibility and reconfigurability in terms of design options. The toolkit components were designed to facilitate multiple and unique combinations, with room for spontaneous design decisions. Our intended participants were novice users so the toolkit was built with familiar materials and techniques involved. Participants also react and respond to materials. So, the material of the toolkit had to be such that it encourages handling and easy manipulation. Artefacts should not be too delicate or too bulky to handle. We selected medium density fiberboard and acrylic sheets for the various components. Both materials are easy to manipulate and can be laser cut. For 3D printed prototypes, we used SDM printers.

The assembly of components was designed to be a simple process that does not put extra cognitive load on participants, or shift them out of their comfort zone. The toolkit is intended for a small group to work on it together so a scale of 1:25 was chosen. Next, all components of the toolkit were listed along with their many permutations and combinations. Some were made in abstract form while others in a more concrete shape. Eg. Concretely defined seats were made with options to be discrete, conjoined, with armrest and bench-type. A participant may not be able to name them or list the category but on seeing them, they would be able to easily select the one they feel most comfortable using. For bus walls, doors and windows, abstract panels of various sizes, both opaque and transparent, were provided, along with channels to slide them into as we did not wish to constrain the number of iterations for entry/exit and outside visibility. Next, dimensions for each component were frozen as per the recommendations in the Indian Bus Code (MoUD, 2013). The Indian Bus Code lists structural, material, ergonomic and dimensional specifications for all public buses that run in India.

The toolkit had both cognitive as well as emotional prompts to facilitate people to access memories and experiences, express their feelings and communicate their aspirations for the future. E.g. Manekin of mother with child, manekin of elderly commuter, wheelchair, stroller, luggage of different kinds, emergency buttons etc. We also included many standing and seated manekins to populate the bus as it was being designed. The male mannequins were included to help bring out the perceptions, attitudes and fears related to male co-passengers. The toolkit included service staff like the driver and the conductor, so as to prompt reflections on their facilitation of women's travel, or the lack of it. In Figure 1 below we see the various parts of the toolkit before assembly.

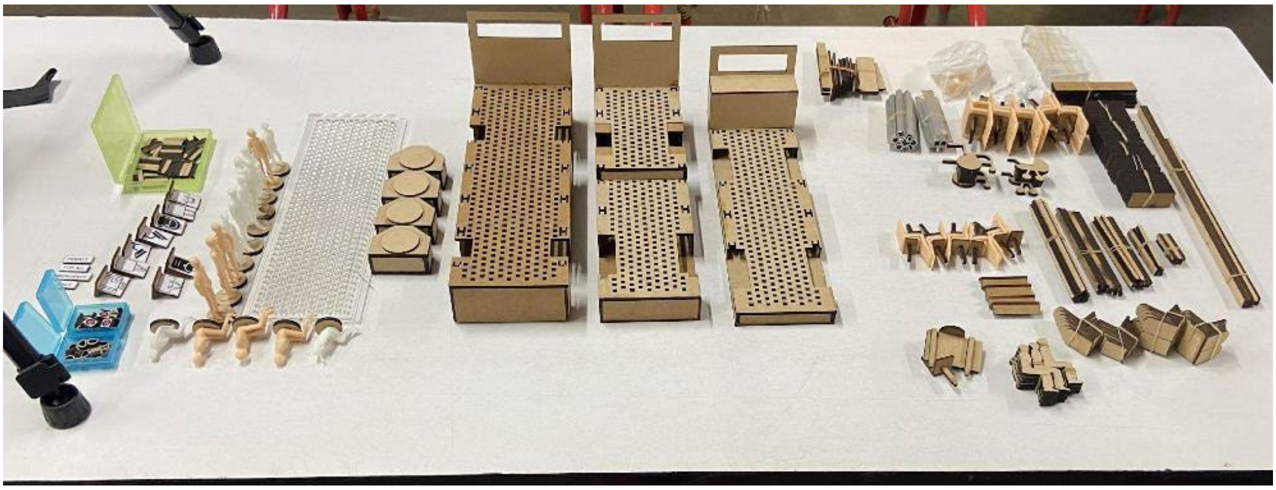


Figure 1: Toolkit laid out during the sensitization session

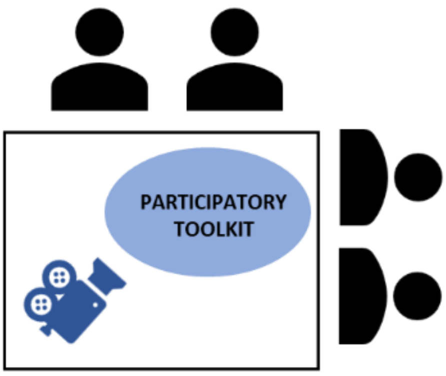
Results & discussion

The rich and complex output of generative sessions generated diverse qualitative data, but the challenge lay in its lack of structure and its spontaneous nature. The designs generated with the toolkit needed to be assessed for motivation, intent and output. The stories and anecdotes recorded while 'making' artefacts also needed to be analyzed. The artefacts and the anecdotes have a complex inter-relationship. So the data generated is complex, fragmented and multilayered. We made exploratory probes into the data, trying to identify main themes. In this section we briefly talk about each workshop, before discussing them in tandem.

Workshop 1 (W1)

4 volunteers joined the pilot workshop. 1 participant was from a metropolitan city while the other 3 were from smaller cities. Participants knew each other beforehand and were comfortable in each other's company. The workshop was held in an informal setting with no distractions or outside noise. An overhead camera was used to record the proceedings. Several stages of the model were captured through photographs separately. The sensitization and the workshop were both conducted in the same space. This was to ensure that participants could look over all the components at leisure. We wanted to build a comfort level with the toolkit beforehand so that the large number of pieces was not overwhelming. We arranged all the components in trays for easy handling.

The sensitization questionnaire warmed up the participants, with some of the participants sharing anecdotes from their hometowns. The researcher's role was to introduce the session and then merely be an observer. On the basis of learnings from the previous pre-pilot workshop, we gave the participants a few basic guidelines to start. The participants concentrated on special needs. They made a decision to reduce the number of seats to 20 so that space could be made for wheelchairs and strollers. The participants tried out some innovative seating layouts but realized their aisle space may be too constrained. They then started using the standing and sitting manekins as 'spacers' between the seats. Figures 2 & 3 below show the workshop setup from WS1.



Figures 2 & 3: Seating Arrangement in Workshop 1

The discussion during the participatory session was rich and spirited. Many past experiences came up during the discussions and participants suggested design features in the bus based on these. The choice of bus platform was very quick and they understood the part played by wheel humps well. The mannequins really helped with building a sense of size which they frequently lost with the space inside the bus. People picked up the spare blank tiles and pipes for various uses without being prompted.

The results from the sensitization as well as the toolkit session were very encouraging. Discussions in both sessions had produced some deep insights. The conversation was consistent throughout the sessions and there were no pauses when participants did not know what to do or how to proceed. We observed no cognitive difficulties in the participants as they interacted with the toolkit. They were able to clearly recognize the abstract forms as well. They made use of the freeform panels to make steps and luggage shelves without being prompted.

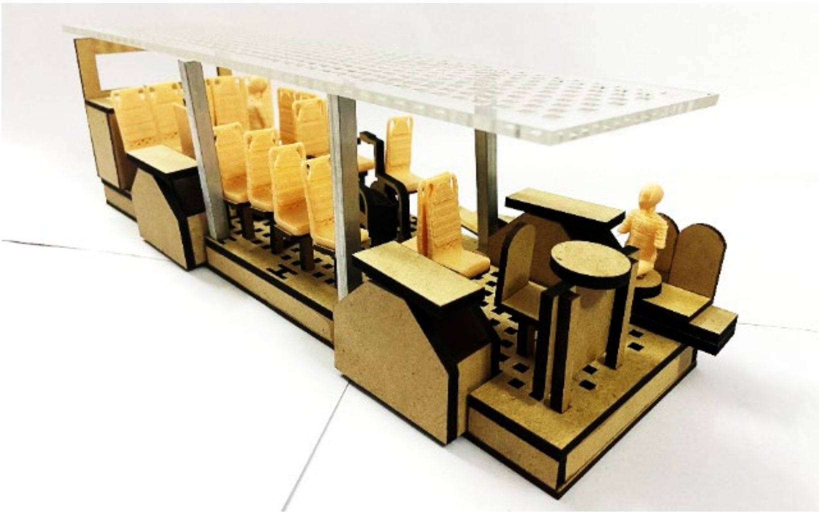
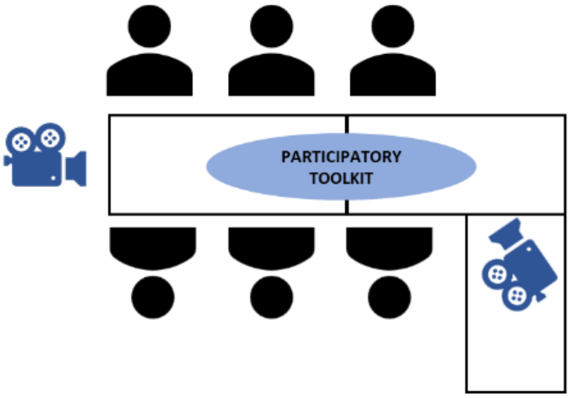


Figure 4: Completed bus design in Pilot 1

Workshop 2 (W2)

This session was attended by four design students and two design faculty members. They were quick to select the low entry bus and place two entry, exit points. After this, some of them picked up the free form panels and started carving out new design solutions. During the sensitization session, many of them had shared traumatic experiences in public buses. Perhaps this spurred them to create a 'happy bus'. The participants wanted to build travel as a playful experience. They said bus travel is an unpleasant experience which isolates one, so they came up with swivelling seats that can turn to face other passengers, and also the window, if one just needs to look into the void for a bit. At a point, however, they rooted out the entire 'scenic' seating and decided to make a more conventional seating layout that accommodated more passengers. They felt the back seats were the worst, furthest away from the driver. They then immediately added a camera and emergency buttons there. They used almost all the different components of the toolkit in their design. Figures 5 & 6 below show the workshop set-up.



Figures 5 & 6: Participant Seating Arrangement in Workshop 2

Standing passengers were given a separate zone as it seems they are the worst offenders when it comes to surreptitious touching and harassment. A participant performed a tiny jig where she made the manekin jump from one pace to the other, peeping down and generally being shifty. They soon realized they had only 14 seats, so they were quick to add a second storey, because 'being happy is more important'. Figure 7 below shows the second seating layout iteration by the group.

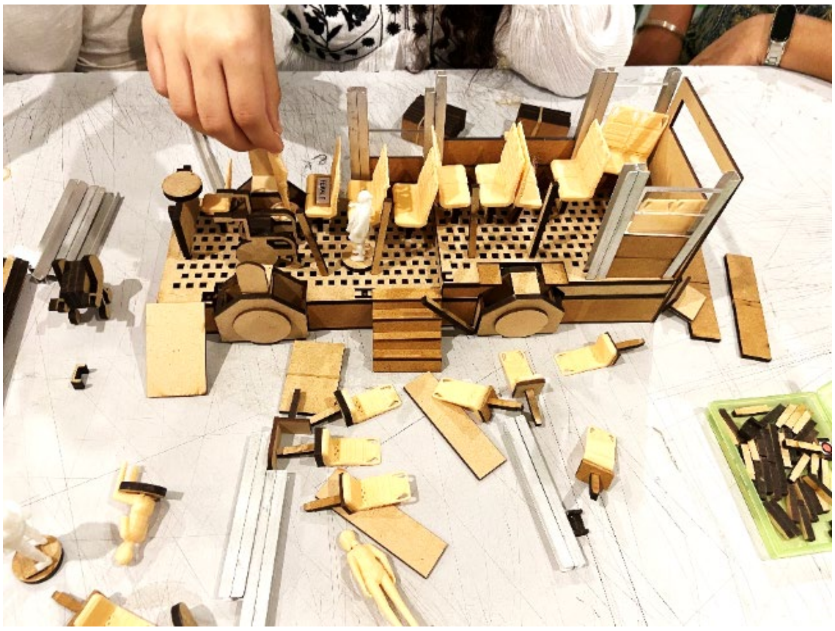
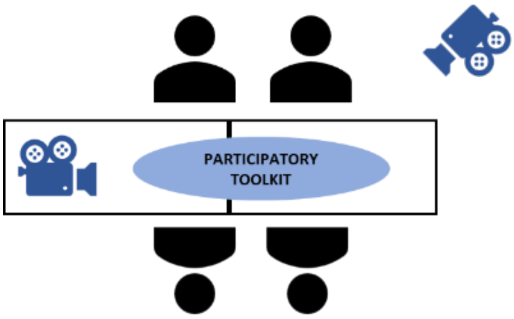


Figure 7: Inclusive design considerations featured prominently in this session

Workshop 3 (W3)

This session had four participants from four different cities, four different age groups and four different professional backgrounds. All had been bus users in the past but were not using buses any more, due to various reasons that ranged from traumatic incidents to car ownership. The sensitization session went on for very long as each participant wanted to tell the story of buses in their city. The group took the longest to make the initial selection of whether to use a high floor, low floor or low entry bus, concentrating on maximum capacity as well as easy access. They selected the low entry bus. Next they worked out the ingress/egress, giving importance to the position of the driver and the conductor. Selection of seats brought up issues of how men and women sit differently in public places. In Figures 8 & 9 below we see the workshop setup.



Figures 8 & 9: Seating arrangement in the third participatory session

The design approach of the participants was significantly different from the first two workshops. They started building the bus from outside inwards. They started by asking how many people the bus is for, probably a reflection of the fact that one participant was faculty in a design college, one from an architecture college, one architecture student and one faculty from an engineering college. They took the 30-person seating capacity as their mandate and kept trying to fit in more and more seats, even while debating the safety and personal space issues.

The discussion during the session was friendly but intense, with the participants going to the crux of the logic behind design considerations very often. Having experienced buses of different kinds in different socio-cultural settings, their reflections were very different. Overall, the concern for systemic design issues was significantly higher than concern for gender specific issues. As a group, their priority was systemic issues of infrastructure, giving maximum design importance to seating layout and accessibility issues.

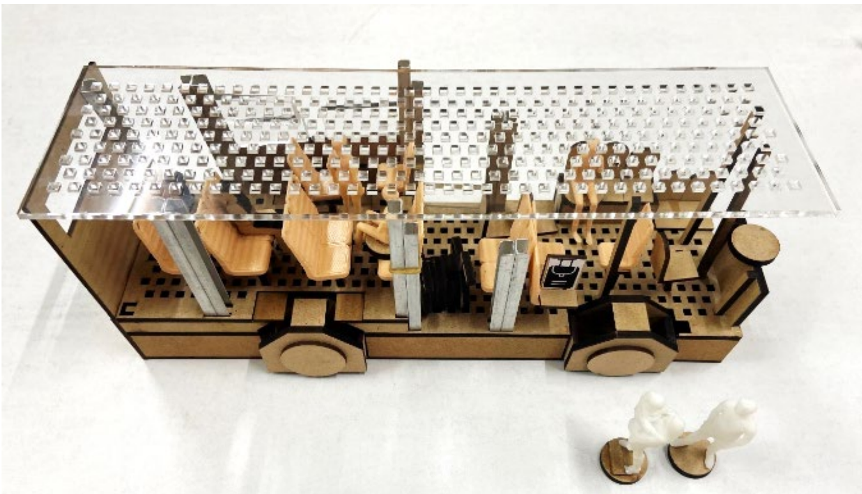


Figure 10: Final prototype generated in the third session

Discussion

We found that the 3D toolkit aided small groups of participants to actively prototype and discuss underlying issues and reasons for their choices. The small group encouraged them to express and speak without reservations. The act of making itself helps keep them focused and involved, utilizing many different faculties at once. The outcome is a manifestation of design considerations through artefacts, arrangements, stories, utterances, anecdotes etc. The sessions produced a rich, but complex set of data which has many layers and is hard to structure.

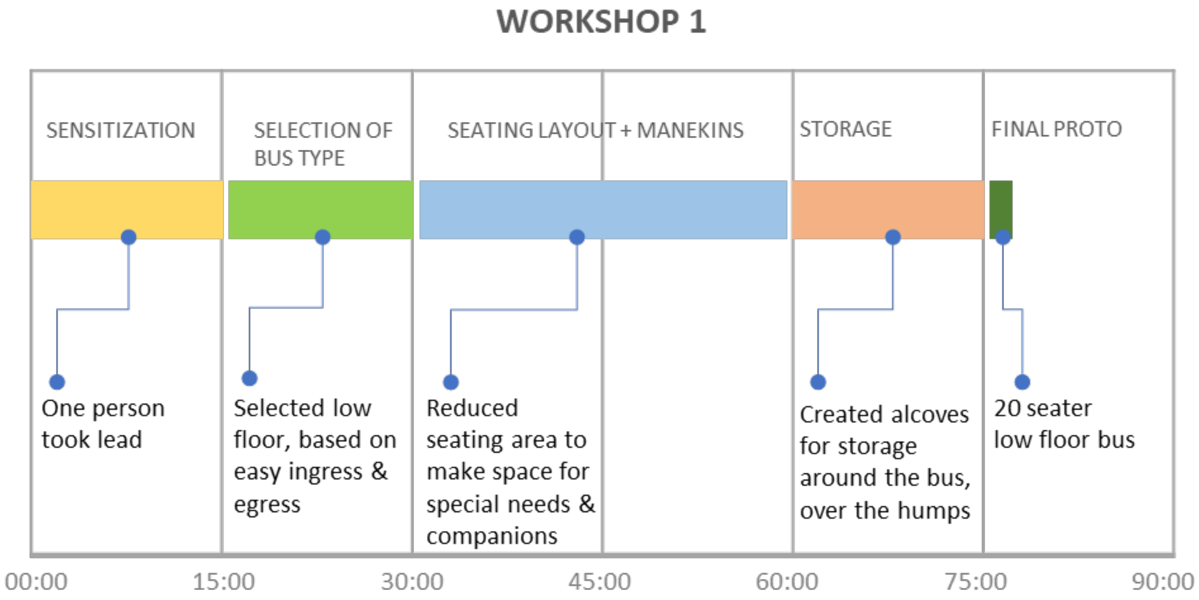
The discussions highlighted the disparity in concerns of women using buses across the country. While women seemed to be most concerned about getting a seat in long commutes in one city, in another, they seemed happy just to get to their destination without any incident of harassment. Where class seemed to matter in one city (bus travel is seen as low class), in another city, it was seen as the quickest way to get from point A to B in morning commutes and used by people across classes. In one city crowds are seen as a safe haven while in another, crowds are seen as a cover for petty crimes and physical harassment.

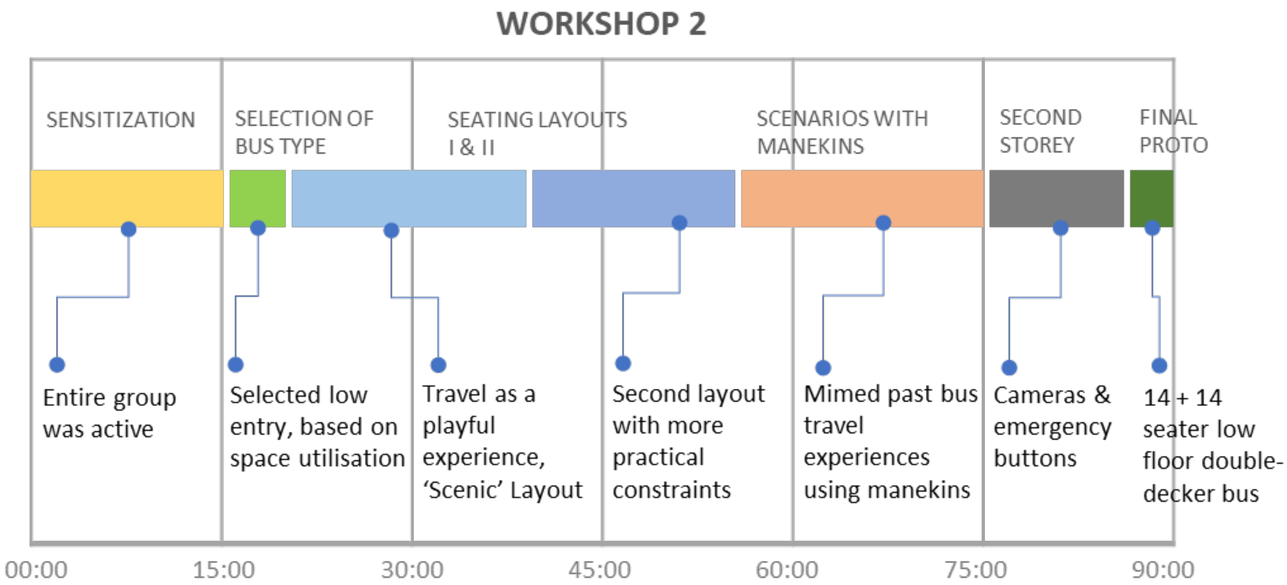
We also observed that travel confidence varied across the participants. They spoke of acquiring travel confidence with age. They were able to voice their complaints to fellow travellers now as compared to when they were younger, but they all also agreed to generally being non-confrontational as they did not want to attract further attention in a public space. They also spoke about feeling more confident when they knew the local language or were travelling in their hometowns. Many of them live in cities away from their hometowns now.

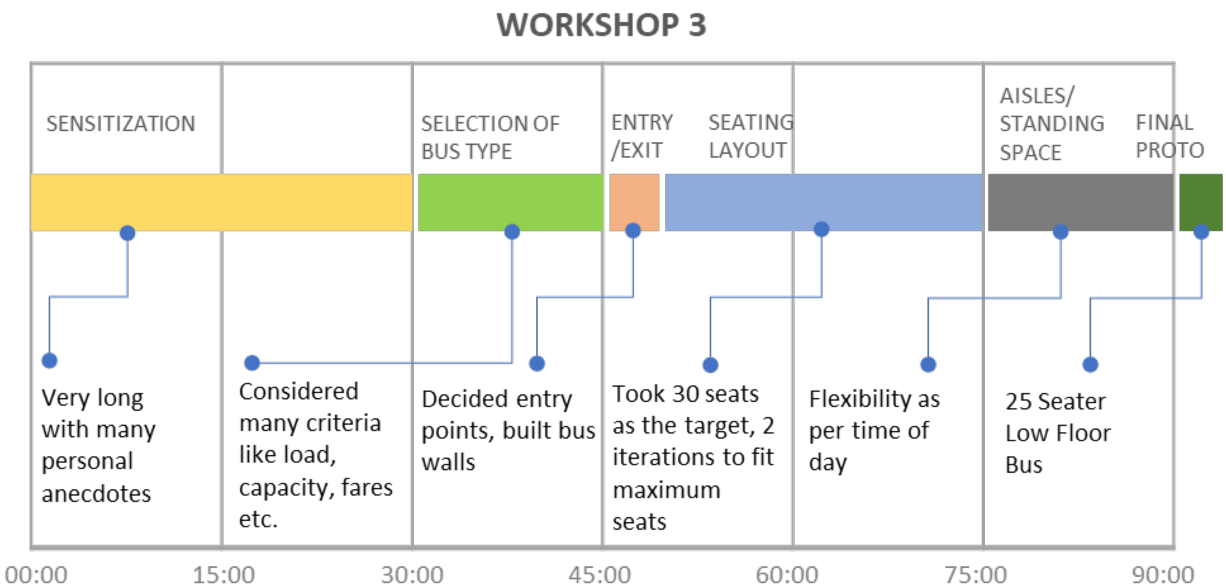
Building prototypes was reminiscent of childhood experiences with building blocks for some of them. Some participants also felt a pressure to be creative. Participants from W2 and W3 mentioned they were not being creative enough. They felt the need to think out of the box and evolve unprecedented designs. W3 participants felt they had sacrificed creativity for pragmatism. They felt their concern of fitting in 30 seats had forced them to be practical and not be able to think unconventionally. The toolkit excited them since most had not built something with blocks since their childhood. It brought back memories of creativity, but discussing the constraints also helped them empathize with the decision makers they said.

The discussions around fellow commuters were also very enlightening. Even though they were very conscious of fellow commuters at all times, avoiding eye contact was a common approach to travel by all the workshop participants. One participant wondered at the irony of not having faith in people but having faith in the red emergency button. The button prompted further reflection where another participant speculated that pushing the button was a 'commitment'; like an official complaint. Almost all participants agreed that they avoid drawing attention to themselves in public transport, even if it meant letting transgressions go.

We analyzed the prototypes created, in conjunction with the stories and discussions shared among the participants. The context of use of buses by women is also manifest in the discussions and the outcomes of the sessions. In the following table, we have explored the timeline of the workshops, the sequence of design activities undertaken, and the main decisions made.


WORKSHOP 1
SENSITIZATION
SELECTION OF BUS TYPE
SEATING LAYOUT + MANEKINS
STORAGE
FINAL PROTO
One person took lead
Selected low floor, based on easy ingress & egress
Reduced seating area to make space for special needs & companions
Created alcoves for storage around the bus, over the humps
20 seater low floor bus
00:00
15:00
30:00
45:00
60:00
75:00
90:00


WORKSHOP 2
SENSITIZATION
SELECTION OF BUS TYPE
SEATING LAYOUTS I & II
SCENARIOS WITH MANEKINS
SECOND STOREY
FINAL PROTO
Entire group was active
Selected low entry, based on space utilisation
Travel as a playful experience, 'Scenic' Layout
Second layout with more practical constraints
Mimed past bus travel experiences using manekins
Cameras & emergency buttons
14 + 14 seater low floor double-decker bus
00:00
15:00
30:00
45:00
60:00
75:00
90:00


WORKSHOP 3
SENSITIZATION
SELECTION OF BUS TYPE
ENTRY /EXIT
SEATING LAYOUT
AISLES/ STANDING SPACE
FINAL PROTO
Very long with many personal anecdotes
Considered many criteria like load, capacity, fares etc.
Decided entry points, built bus walls
Took 30 seats as the target, 2 iterations to fit maximum seats
Flexibility as per time of day
25 Seater Low Floor Bus
00:00
15:00
30:00
45:00
60:00
75:00
90:00

We found that each workshop progressed in a unique manner. While the first group was very target oriented and concentrated on meeting the special needs, the second group decided to concentrate on mental well being and a happier travel experience. The third group took the pragmatic approach and tried to consider infrastructural requirements along with safety measures. Each group built their prototype differently. While the first two groups took an inside-outwards approach, freezing the layout before managing entry points, windows etc, the third group built outside-inwards, freezing all structural points before the seat layout. The first group made quick decisions with one prominent participant at the helm, but this changed in the latter half when the others started speaking up as well. The second group set themselves the mandate of being happy and tried to make the antipodes of current buses. The third group moved only after much deliberation and discussion, so took the longest time, but also came up with the most pragmatic, immediately implementable solutions. The conversation highlighted issues of ventilation and temperature, as per the seasonality of use. Accessibility was indicated as a challenge by almost all, quoting issues of overcrowding, one's own large frame, balance issues etc. Access to those with special needs was seen as a privilege. In all three workshops, there was constant discussion and telling of anecdotes.

In the toolkit itself, the participants pointed out that they would like even more flexibility in the floor grid for more varied layouts.They also asked for a more flexible wall panelling sytem to create a more innovative outer shell for the bus.

Conclusion

We undertook this research to create a participatory toolkit that would help women bus users share their issues and aspirations in using public transport in India. The DIY bus model was meant to create a sort of sandbox where participants from different backgrounds came together to find common ground to exchange or generate knowledge as they worked on a common goal, building their dream bus.

Although generative design techniques have been shown to bring out novel and unconventional design solutions, the three groups did not come up with any strikingly new designs, but what was enlightening was their conversations and anecdotes as they put together their DIY buses. Each group followed a distinct design strategy and had different priorities. The participatory toolkit served as a boundary object that helped generate new insights into the participants' lived experiences, giving a tangible form to the abstract concepts in their minds. The group discussions brought many tacit needs to fore, giving voice to the unarticulated thoughts of the participants. The workshops gave us insights into their current preoccupations and also future aspirations. In future work, we intend to transcribe the recordings from all the workshops and analyze them using grounded theory to discover structures and themes without the burden of pre-set expectations. The aim is to eventually develop a framework that helps address lacunae in public transport based on findings from participatory workshops that engage citizens.

References

Akkerman, S. F., & Bakker, A. (2011). Boundary crossing and boundary objects. Review of educational research, 81(2), 132-169.

Baldassarre, B., Konietzko, J., Brown, P., Calabretta, G., Bocken, N., Karpen, I. O., & Hultink, E. J. (2020). Addressing the design-implementation gap of sustainable business models by prototyping: A tool for planning and executing small-scale pilots. Journal of Cleaner Production, 255, 120295.

Bamberger, M., Lebo, J., Gwilliam, K., Gannon, C. (1999). Gender and Transport : A Rationale for Action. In PREM Notes; No. 14. World Bank, Washington, DC. © World Bank. Retrieved from https://openknowledge.worldbank.org/handle/10986/11504 License: CC BY 3.0 IGO

Borum, N., Petersson, E., & Frimodt-Møller, S. (2014). The Resilience of Analog Tools in Creative Work Practices. International Conference on Human-Computer Interaction (HCI 2014), 8510, 23–24.

Bowker, G., & Star, S. L. (1999). Sorting things out. Classification and its consequences, 4.

Dhaundiyal, D., & Sharma, N. (2022a). Tacit need capture through participatory research to increase female access to public transport in new Indian cities, RGS-IBG Annual International Conference 2022: Participatory methods for recovery and transformation, Royal Geographical Society (with the Institute of British Geographers), 30 August-2 September, 2022

Dhaundiyal, D., & Sharma, N. (2022b). Exploring Boundary Objects in Artefact Based Probes in Capturing Tacit Knowledge. In Proceedings of the Participatory Design Conference 2022-Volume 2 (pp. 208-209).

Dunne, A., & Raby, F. (2013). Speculative everything: design, fiction, and social dreaming. MIT press.

Fong, A., Valerdi, R., & Srinivasan, J. (2007). Boundary objects as a framework to understand the role of systems integrators. In Systems Research Forum (Vol. 2, No. 01, pp. 11-18). World Scientific Publishing Company.

Groot, B., & Abma, T. (2021). Boundary objects: Engaging and bridging needs of people in participatory research by arts-based methods. International Journal of Environmental Research and Public Health, 18(15), 7903.

Hamilton, K. and Jenkins, L. (2000). A Gender Audit for Public Transport: A New Policy Tool in the Tackling of Social Exclusion, Urban Studies, 37(10), pp. 1793–1800. doi: 10.1080/00420980020080411.

Hsiao, R. L., Tsai, D. H., & Lee, C. F. (2012). Collaborative knowing: the adaptive nature of cross‐boundary spanning. Journal of management studies, 49(3), 463-491.

Huang, E. Y., & Huang, T. K. (2011, January). Antecedents and outcomes of boundary objects in knowledge interaction in the context of software systems analysis. In 2011 44th Hawaii International Conference on System Sciences (pp. 1-9). IEEE.

Huvila, I., Anderson, T. D., Jansen, E. H., McKenzie, P., & Worrall, A. (2017). Boundary *objects in information science. Journal of the Association for Information Science and Technology, 68(8), 1807-1822.*

Impedovo, M. A., & Manuti, A. (2016). Boundary objects as connectors between communities of practices in the organizational context. Development and Learning in Organizations: An International Journal, 30(2), 7-10.

Kanwal, S., Nunes, M. B., Hui, M. A. C., & Madden, A. D. (2019). Application of boundary objects in knowledge management research: A review. Electronic Journal of Knowledge Management, 17(2), pp100-113.

Kanwal, S., Nunes, M. B., Hui, M. A. C., & Madden, A. D. (2019). Application of boundary objects in knowledge management research: A review. Electronic Journal of Knowledge Management, 17(2), pp100-113.

Star, S. L. (1999). The ethnography of infrastructure. American behavioral scientist, 43(3), 377-391.

Star, S. L. (2010). This is Not a Boundary Object: Reflections on the Origin of a Concept. Science, Technology, & Human Values, 35(5), 601–617.

Liu, W., Zhu, Y., Liu, M., & Li, Y. (2022). Exploring maker innovation: A transdisciplinary engineering design perspective. Sustainability, 14(1), 295.

Lockton, D. (2017). Design, Behaviour Change, and the Design with Intent Toolkit. In: Niedderer, K., Clune, S.J., Ludden, G. (Eds.), Design for Behaviour Change: Theories and practices of designing for change. London: Routledge

McCusker, S. (2020). Everybody's monkey is important: LEGO® Serious Play® as a methodology for enabling equality of voice within diverse groups. International journal of research & method in education, 43(2), 146-162.

Melo, S., & Bishop, S. (2020). Translating healthcare research evidence into practice: The role of linked boundary objects. Social Science & Medicine, 246, 112731.

MoUD. (2013). Urban Bus Specifications II. https://mohua.gov.in/upload/uploadfiles/files/Urban-Bus-Specifications-II.pdf

Oswick, C., & Robertson, M. (2009). Boundary objects reconsidered: From bridges and anchors to barricades and mazes. Journal of Change Management, 9(2), 179-193.

Pas, E. (1984). The effect of selected socio-demographic characteristics on daily travel behaviour. Environment and Planning, A 16, 571–581.

Peters, D. (2015). Gender and Transport in Less Developed Countries : A Background Paper in Preparation for CSD-9. (August).

Peters, D., Loke, L., & Ahmadpour, N. (2021). Toolkits, cards and games–a review of analogue tools for collaborative ideation. CoDesign, 17(4), 410-434.

Sanders, E. B. N., & Stappers, P. J. (2014). Probes, toolkits and prototypes: three approaches to making in codesigning. CoDesign, 10(1), 5-14.

Schindler, J. (2015). Expertise and tacit knowledge in artistic and design processes: Results of an ethnographic study. Journal of Research Practice, 11(2), M6-M6.

Sleeswijk-Visser, F., Stappers, P. J., Van Der Lugt, R., & Sanders, E. B. N. (2005). Contextmapping: Experiences from Practice. CoDesign: International Journal of CoCreation in Design and Arts, Vol. 1 No. 2.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social studies of science, 19(3), 387-420.

The LEGO Group (2010). LEGO Serious Play Material. Retrieved from: https://www.lego.com/en-us/seriousplay/material

Tsekleves, E., Darby, A., Ahorlu, C., De Souza, D., Pickup, R., & Boakye, D. (2019). Combining design research with microbiology to tackle drug-resistant infections in different home environments in Ghana: Challenging the boundaries of design thinking. The Design Journal, 22(sup1), 347-358.

Turner, J. and Grieco, M. (2000). Gender and Time Poverty: The Neglected Social Policy Implications of Gendered Time, Transport and Travel, Time & Society, 9(1), pp. 129–136. doi: 10.1177/0961463X00009001007.

Välk, S., Maudet, N., & Mougenot, C. (2019). Exploring how boundary objects can support multidisciplinary design and science collaboration. International Association of Societies of Design Research.

Dhriti Dhaundiyal

Dhriti Dhaundiyal completed her graduation in Design from National Institute of Design, India and her post-graduation is in Sustainability Studies from King's College, UK as a Chevening scholar. She has previously worked as an automobile designer in India and Japan for Tata Motors, Maruti Suzuki India and Suzuki Japan for over six years. She is currently working as an Assistant Professor in School of Design in Doon University where she has been teaching for the last decade. Her ongoing doctoral research is on inclusive public transport in India using participatory methods.

Nishant Sharma

Nishant Sharma is a Professor of Mobility & Vehicle Design at IDC School of Design, IIT Bombay. With a strong focus on Vehicle Form & Aesthetics, Mobility Design, and Participatory Design, he has played a pioneering role in shaping India's first specialized Transportation & Automobile Design program at the National Institute of Design, Ahmedabad, and establishing the Mobility and Vehicle Design program at IIT Bombay. As an educator and researcher, he teaches postgraduate courses, supervises Master of Design and PhD students, and leads funded research and consultancy projects with government, private companies, and non-governmental organizations. His expertise in Bionics, Human-Powered Mobility, and Nature & Form has cemented his position as a leading figure in mobility and vehicle design in India.

Using machine learning as a material to generate and refine aircraft design prototypes

Linus Tan, School of Design and Architecture, Swinburne University of Technology + Aerostructures Innovation Research (AIR) Hub, Swinburne University of Technology
Thom Luke, Aerostructures Innovation Research (AIR) Hub, Swinburne University of Technology + School of Design and Architecture, Swinburne University of Technology
Adriano di Pietro, Aerostructures Innovation Research (AIR) Hub, Swinburne University of Technology
Anita Kocsis, Swinburne Design Factory Melbourne, Swinburne University of Technology

Abstract

In this paper, we explore the role of machine learning (ML) as a design material in prototyping new aircraft designs. This will be increasingly significant in the future, as new industry looks to meet the emerging demands of Advanced Air Mobility (AAM). With increasing budget constraints, regulations and lengthy certification processes, traditional aerospace companies invest the majority of their efforts in prototyping incremental improvements of their existing aircraft designs. Many such prototyping efforts focus on producing (e.g. rapid prototyping and additive manufacturing) and evaluating (e.g. modelling and simulation) to optimize designs. The investment to explore different aircraft designs pales in comparison. The public release of ML software presents an opportunity for aircraft designers to prototype novel designs with little financial investment and at a faster rate. Our design-led research uses Stable Diffusion, a text-to-image ML software, to prototype such designs. Our findings show how the software can behave in two different ways; generate a variety of prototypes and refine prototypes towards a makeable object. Based on our findings, we recommend designers looking to introduce ML into their design and prototyping process to maintain opportunities for the software to influence the prototyping direction, as opposed to using it as a means of producing many prototypes.

Machine learning; generating prototypes; refining prototypes; aircraft design

With the recent public releases of multiple ML software that converts text prompts into images, designers can now use AI to synthesize large visual data sets without having to understand or design the technical aspects of the software. Projects using ML are starting to appear in many of the design fields, such as in urban design (e.g. Sidewalk Labs, 2022), architecture (e.g. SPAN, 2020), product design (e.g. STARCK, 2020), engineering design (e.g. Hyperganic Group, 2021), and performance design (e.g. Choy, 2021), to name a few. Such ML-driven design projects have led to a media surge regarding the impact of ML in the future of design, as evidenced on popular blogs like Dezeen (e.g. Dreith, 2022), Archdaily (e.g. Florian, 2022), and designboom (e.g. Khan, 2022).

Such discussions have emerged in design research too. There is a growing interest in the human-computer interface community to use AI as tools (Holmquist, 2017) in the processes of UX, UI, interaction, and service design. Generally in the design literature, research interest ranges from creating conceptual models that describes how to collaborate with AI systems in design (e.g. Koch, 2017; Wu et al., 2021), to integrating ML into design methodologies (e.g. Luhrs & Tan, 2022; Yang, 2018). However, Mateescu and Elish (2019) argue for increased focus on how AI is integrated into design research and practice, for despite the increasing research on ML techniques themself, there is still a literature gap on how designers use AI, specifically in generating design ideas (Chen et al., 2019) and integrating in prototypes and products (Malsattar et al., 2019).

Our study responds to this gap by discussing our process using Stable Diffusion, a text-to-image ML software, as a design material to generate and refine prototypes for early-stage aircraft designs. Specifically, this research contributes to the exploration of how ML software can be used in the prototyping process. Our study is guided by two research questions. Firstly, how can ML **generate** prototypes based on the designer's text prompts? Secondly, how can ML **refine** prototypes towards a makeable design. This question seeks to identify how the ML outputs prompt the designer to evaluate and refine the AI-generated ideas. Our study contributes evidence-based guidance to help future designers adopt ML software in their design and prototyping processes.

Background

To understand how designers and design researchers use ML in their projects, the section below describes the current literature on 1) how designers can use ML software as a material in the design process, 2) what designers are using ML for in design and prototyping, and 3) the challenges of using ML software to prototype designs. Finally, we explain why using ML as a design material should be framed design as reflective practice.

ML software as a design material

In design research and practice, the materials that designers work with have the potential to influence and change the design processes (Karana et al., 2019). While designers choose materials to execute their design concepts, they can also interrogate the properties of the material at hand to produce a design concept (Nimkulrat, 2009). For example, designers can leverage properties, particularly those of emerging and digitally augmented materials, to deliver a new experience for the user of the design product.

While such materials are often in reference to tangible materials, intangible materials are also another class of design material to consider. Specifically, the intelligence behind the software is the material (Holmquist, 2017) for designers to experiment and use. While designers working to produce physical outcomes may find this difficult to work with, digital designers already treat some software as an 'immaterial' design material (Ozenc et al., 2010). As Yang (2018, p. 468) argued, ML is not just a tool but a design material, for:

> *"When taking a technology as a design material, designers first develop a tacit understanding of how the technology opens up and constraint design possibilities.*

They then innovate by engaging in reflective conversations with design materials, envisioning things that have never before existed.”

Using ML software to prototype designs

There are many design research and practice projects that already use ML in the design process. These projects generally fall into two categories, refining designs and generating ideas. This is unsurprising as the key advantage of ML is its ability to interpret ambiguous prompts from the software user to detect patterns in large data sets (Murphy, 2012). Thus, ML can evaluate complex designs quickly to identify patterns and anomalies, which then enables designers to refine their design prototypes. Examples of these projects include optimizing structural loading of architectural prototypes (Tamke et al., 2017, 2018) and refining the performance of a design installation in different environmental conditions prior to construction (Wilkinson et al., 2014). ML-powered image generating software makes it quicker to visualize ideas, as they can synthesize large visual data sets to produce an image based on ambiguous prompts from the designer. These almost instant visualizations then become cues for the designer to either interrogate further or scope out different ideas during the ideation phase. Some of these projects include using ML to evaluate a range of design projects to generate novel conceptual designs (As et al., 2018), using ML to synthesize images of two distinct architectural types to create new architectural forms (del Campo et al., 2019), and using ML to generate a chair design fit for fabrication (STARCK, 2020). In fact, Luhrs and Tan (2022) even used ML to refine and generate designs in prototyping their design proposals. They used MidJourney, a ML text-to-image generating software, to 1) refine a user persona through the triangulation of different generated user experiences, and 2) generate a range of different spatial designs based on rearranging and using different design feature keywords.

Challenges using ML software to prototype designs

But integrating ML in the design process is not as straightforward as these projects make it out to be. A survey of 51 user experience designers indicated that the majority of participants found it challenging to work with ML as a design material (Dove et al., 2017). This was because more often than not, the AI outcomes are unpredictable (Holmquist, 2017), which made it challenging for the designers to wield ML software as design tools as they often require coherence in their practice. Perhaps this can explain the gradual emergence of tools to facilitate designers in using ML in their projects. These tools include, but are not limited to a card deck that simplifies the technical language behind ML for designers to generate ideas and prototype designs that leverages ML (d.School, 2018), a toolkit based on a shared language between technical experts and designers for non-tech experts to integrate ML concepts into the projects (Futurice, 2020), and a card deck for designers to generate ideas that leverage ML technology (Try Tiggers, 2020). Nonetheless, another survey of 46 professional designers indicated a positive and pragmatic attitude towards collaborating with AI software (Main & Grierson, 2020). This survey also revealed that designers perceive that AI was more apt at researching the brief than at generating concepts, for the former required lesser creativity than the latter.

Reflective practice with ML software

Based on the concept of ML software as a design material, we adopt the design theory of reflective practice (Schön, 1983, 1992; Tan et al., 2023), and that designers converse reflectively with their design materials (Schön & Bennett, 1996). Design as reflective practice implies that designers iteratively 1) reflect on the design material they are working on, 2) make a move to change the material, and 3) reflect again this time on the second iteration of the material, to design. On a detailed level, designers reflect-in-action to make subconscious decisions when designing and reflect-on-action after completing a design to evaluate their own work (Schön, 1983). Since ML software produces outputs that respond to the designer prompts, each output delivered is a new piece of information for the designer to converse reflectively with the design process. Hence, the ML software is a material, which can act as *instruments of inquiry* to support designers in ideating and exploring in the design space (Dalsgaard, 2017). Thus, when designing with ML software, the designer sees what the software produces, adjusts and re-prompts the software and then evaluates the outcome (Aranda-Muñoz et al., 2022) iteratively to develop a design.

Research Design

We conducted design-led research to explore, document, and analyse how ML is used as a design material. We used Stable Diffusion (SD), a mainstream text-to-image AI generator (Stability.ai, 2022) to generate and refine aircraft design prototypes. Our data included 1) the text prompts used, 2) prototypes generated, and 3) the reflective conversations between us, the designers, and the ML generated prototypes.

Reflective practice execution

Author 1 is reflective practice researcher (see Tan, 2021) and uses machine learning software to augment design processes. Author 2 has a background in industrial design and aerospace design. Author 2 used the material, Stable Diffusion, to generate the prototypes (data source 2). After generating several prototypes, both authors reflected-on-action to examine how the material responded to the different textual prompts. Both authors also, to an extent, reflected-in-action by comparing the prototypes and querying what in the prompts enabled the prototypes to be different (data source 3). Based on the reflective conversation between the authors and the material, we developed the next iteration of prompts (data source 1) and repeated this process systematically. Author 3 is an aerospace industry design innovator and Author 4 is a design innovation researcher. They reviewed the research from their individual disciplines to ensure aerospace design and research process relevance respectively.

Research context – Aerospace design

Before delving into the findings, we explain the current aerospace design context. With increasing budget constraints, regulations and lengthy certifications processes, many traditional aerospace companies invest majority of their efforts in prototyping incremental improvements of their existing aerospace designs (Church, 2019). Many of such prototyping efforts focused on producing (e.g. rapid prototyping and additive manufacturing) and evaluating (e.g. modelling and simulation) to optimize designs. A prototyping production example is the Evolved Structures prototyping process, by NASA. This process uses AI to design parts that look “alien and weird”, but can save up to two-thirds of the typical weight without sacrificing functional performance (Hille, 2023). Such components are then 3D printed and tested to improve the overall aerospace design performance. A prototyping evaluation example is Advanced Teaming Integration Lab, by Boeing Company. They integrated AI technology into their flight simulators to learn and adapt to the user’s operation behavior, which in turn “fills the development gap between pure simulation and flight test” and speeds up their design-build-test prototyping process (Aurora Flight Sciences, 2022; Zimmer, 2023).

The investment to explore new forms of aircraft designs in the early stage of the design process pales in comparison. Despite already investing AI in the simulations, Boeing Company’s CEO announced in 2014 that their focus is on regular and incremental innovation rather than technological “moon shots” (Ostrower, 2015). This is mostly due to the need to reduce production cost and time so as to maintain financial feasibility with operations. With the public release of ML software, aerospace designers can explore, generate, and refine radical designs with little financial investment and at a faster rate. Rather than use ML software to prototype incremental design improvements, one of our design brief requirements was to incorporate biomimicry prompts as an attempt to find novel ideas of aircraft design inspired by nature.

Results

We conducted 70 material experiments and produced a total of 485 image prototypes of aircraft designs. These experiments were to 1) understand the material characteristics of SD, 2) identify the strengths and weaknesses of the material properties, and 3) develop a prototyping workflow that integrates SD as a design material. Below describes 16 of our experiments to show how we used SD to prototype aircraft designs. Examples 1 – 3 describe how SD: 1) creates prototype variety, 2) creates feasible prototypes, and 3) maximizes the number of prototype designs with minimal inputs. Examples 4 and 5 describe how SD: 1) refines prototypes using image references, and 2) reference prior outputs to refine future prototypes. Example 6 describes our final SD workflow for generating and refining aircraft design prototypes through to making a physical model.

Example 1: Creating prototype variety

In our early phase experiments, we prompted SD with “*Plan view of a bird inspired airplane, biomimicry, engineering drawing, detail, 8k, bird, feather, materials, innovation*” to generate prototypes. We used multiple keywords as many ML prompt examples online used this method to achieve high fidelity outputs. Our prototypes varied largely and lacked complexity (see Figure 1). The prototypes also missed the key intentions of our prompt and produced ambiguous prototype representations.

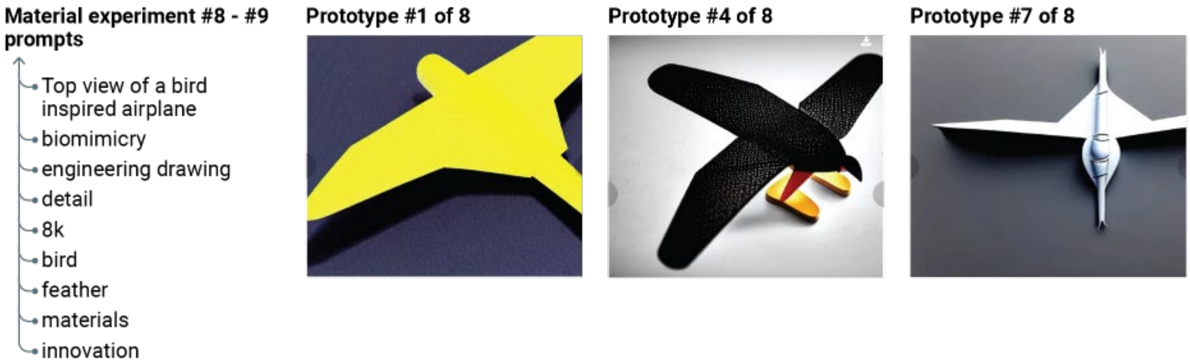


Figure 1: Variety of potential prototypes

While these prototypes were unpredictable to an extent, the results enabled us to scope multiple directions in order to develop different prototypes in subsequent experiments. In Figure 1, the prototypes indicated different prototyping techniques, such as a paper model (Prototype #1) and a laser cut model (Prototype #4). While we did not capture these prototyping qualities in the prompts, the outcomes showed us how to stimulate SD in future experiments. At this stage, the prototypes created based on our ambiguous key words were abstract enough to suggest ways of developing better prototypes, but not concrete enough to be made as a physical prototype.

Example 2: Creating feasible prototypes

In another experiment, we used the prompt "*Top side and front view an airplane inspired by a pelican, engineering drawing, 3 views, detail*". We selected these keywords to make SD produce prototypes that would show basic engineering drawings of an airplane. We also prioritized "*Top side and front view*" and expected SD to provide CAD-like details that would enable us to conveniently translate it into CAD drawings for making a physical prototype. Despite prioritizing "*Top side and front view*", the SD iterations were still too abstract for us to develop them into higher fidelity prototypes (see Figure 2).

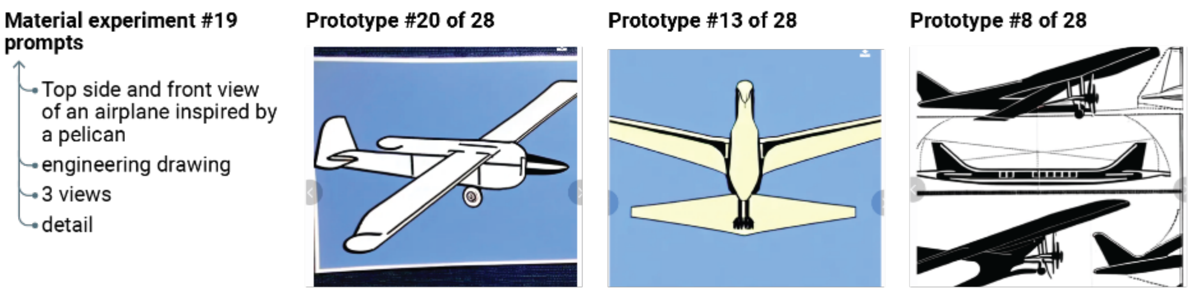


Figure 2: Abstract prototypes generated by SD

However, we noticed that many of the prototypes resembled "laser cut-able" models or showed components that appeared to be laser cut. While our original objective did not intend for the prototypes to be made by laser cutting, the prototype representations guided us to explicitly use "laser cut" in subsequent experiments. Thus, we replaced "top side and front view” with “laser cut” and used “Kit of *laser cut parts of airplane inspired by a bird, engineering drawing, 3 views, detail”*. This change in prompt led to a developmental leap in the prototypes (see Figure 3). These prototypes now more accurately reflected our prompts of an aircraft design inspired by a bird, specifically in the structure. While these prototypes were not presented as 3 view drawings, they now exhibited manufacturing feasibility detail for physical prototype execution.

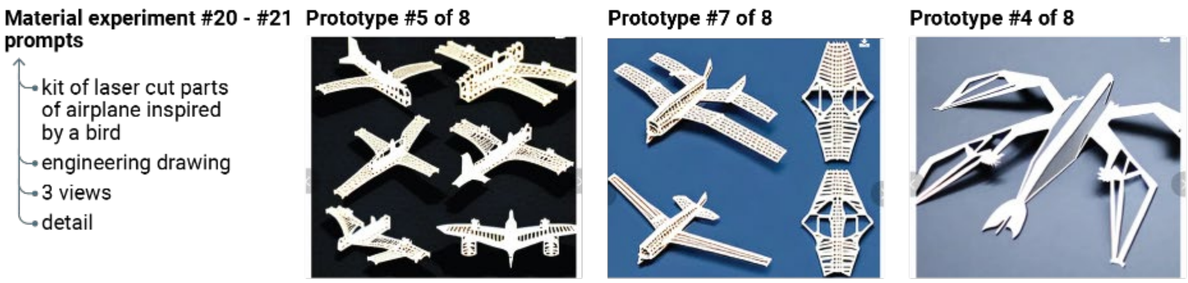


Figure 3: Adding making technique into the prompt

Example 3: Maximizing variety with minimal input

When we compared Examples 1 and 2, we found that SD only responded to certain keywords to produce the prototypes. Therefore, we minimized the keywords used in our prompts and instead played with the pairing of keywords to maximize the number of prompts. With three animal references (pelican, hummingbird, and bat) and three prototyping techniques (origami, laser cut, 3d printing), we ended up with nine experiments which produced 81 prototypes (see Figure 4).

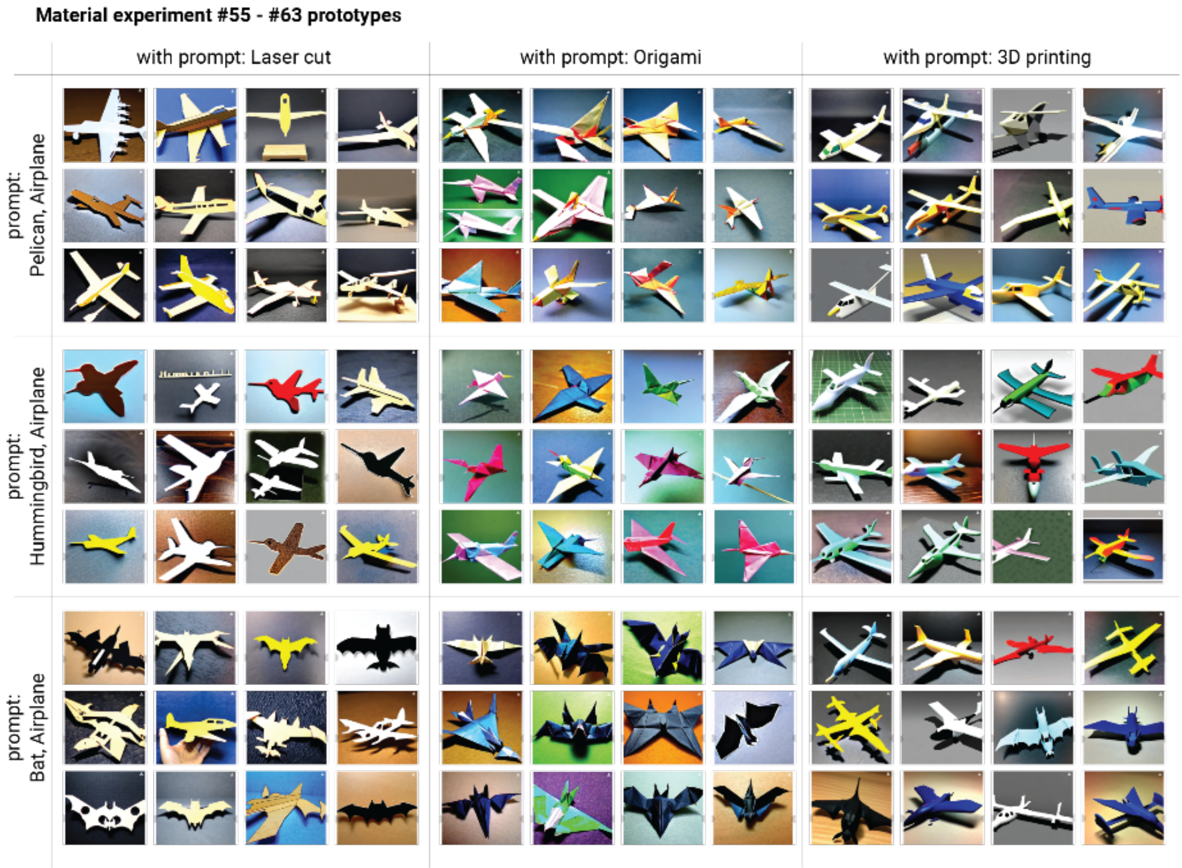


Figure 4: Cross pairing of keywords to produce different prototypes

By using fewer keywords, the prototypes showed greater detail, feasibility, and reflected more accurately the intent of the prompt. However, this raised a challenge with using SD to create prototypes – adding more keywords to the prompt may not refine the prototypes but instead, make the outcomes more abstract. Thus, we experimented with SD to find ways of refining the prototypes.

Example 4: Refining prototypes using image references

Example 1 – 3 experiments used only text prompts to generate prototypes. However, another SD material feature is adding images to supplement the text prompts. Hence, we included images in subsequent experiments to assess how it refined the prototypes produced. To test how images refined the prototypes, we used the same prompt from a previous experiment and added a schematic drawing of the half-A-Delta airframe (see Figure 5). We chose this image as we expected SD to innovate these drawings with biomimetic qualities. We also chose this image because the drawings alluded to laser cut pieces and we expected SD to produce CAD-like drawings for us to make laser cut prototypes.

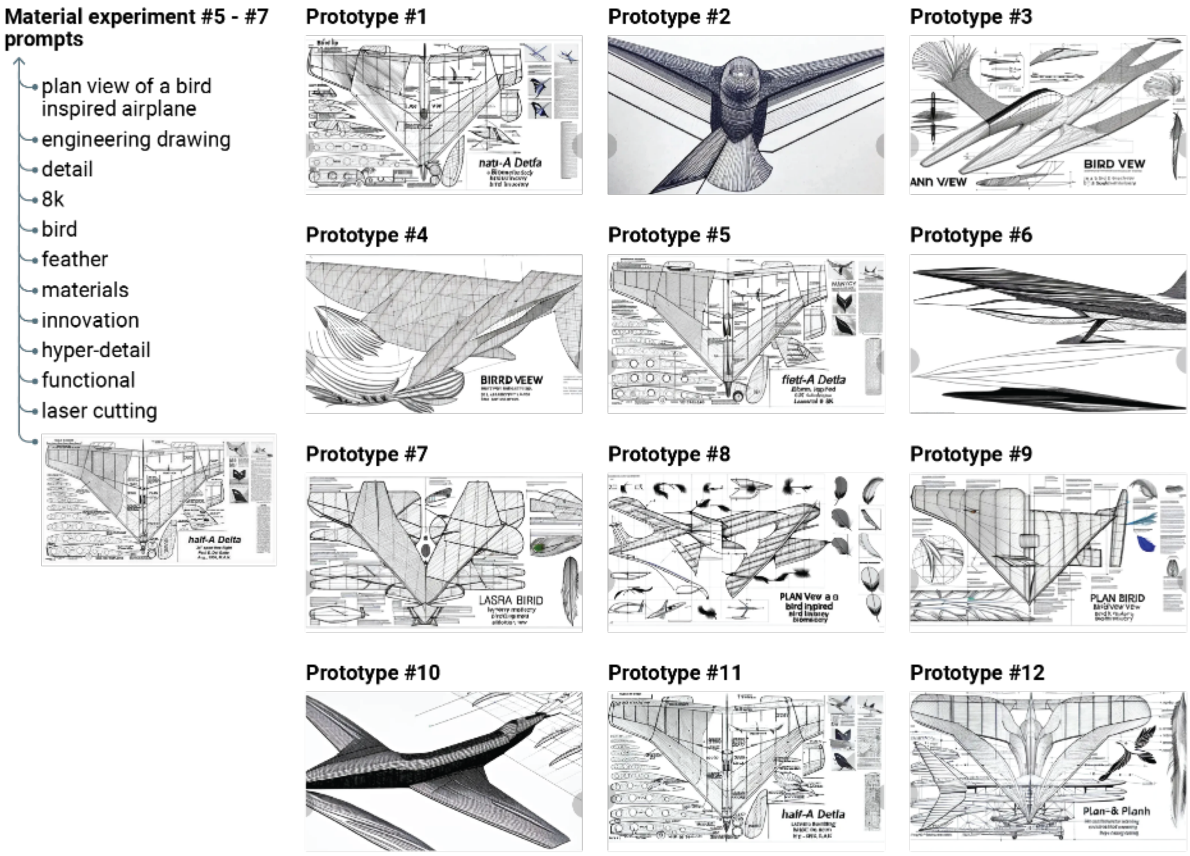


Figure 5: Using images to refine our prototypes

As expected, the SD prototypes retained a visual likeness to the original image input; the black and white scheme, matching line weights, and crosshatching. Additionally, SD made significant changes, as prompted by our keywords, to the prototypes (see Figure 6). It appeared that SD relied heavily on the image input to produce the output aesthetics, then integrated elements of the text prompts "bird, biomimicry, feather" into the prototypes.

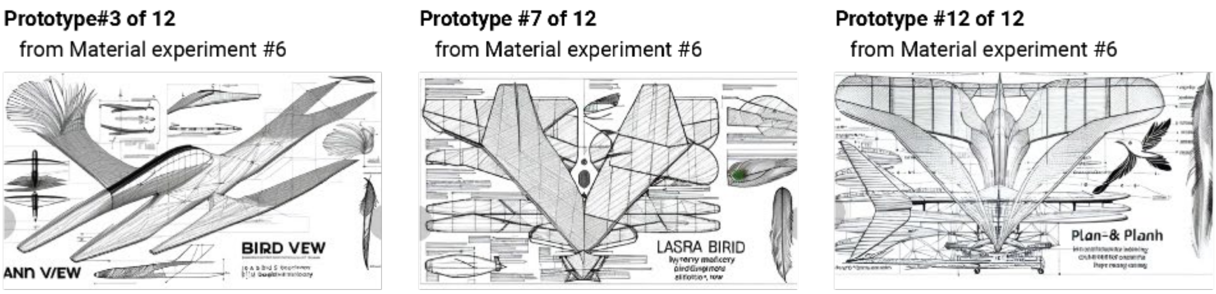


Figure 6: Prototype refinement by SD

For example, in Figure 6, "feather" appeared explicitly in the three prototypes, "bird" was mentioned explicitly in Prototype #3 and #7 and an image of a bird was visualized in Prototype #12. The prompt "biomimicry" remained less clear in the prototypes, which may have been due to the word's abstract nature. However, we observed 1) the overall plane structure of the prototypes shared similarities with bird skeletal structure, 2) beak-like features appeared in Prototype #3, and 3) wing-to-body bird mechanisms appeared in Prototype #12. This method saw a significant leap in definition and quality from our earlier prototypes that had not leveraged an input image in the generation process.

Example 5: Referencing prior outputs to refine future prototypes

The previous example showed us that using an image to supplement our text prompts produced images of high-fidelity prototypes. Thus, we referred to our prior experiments that used SD to create prototypes (refer to Example 1 – 3) and searched for suitable SD produced images that would be suitable as references for our subsequent experiments (see Figure 7). These earlier prototypes that had been generated using text prompts only, were then substituted in replacement of the image we had sourced of the “Half-a” delta design that we had used in our earlier experiments.

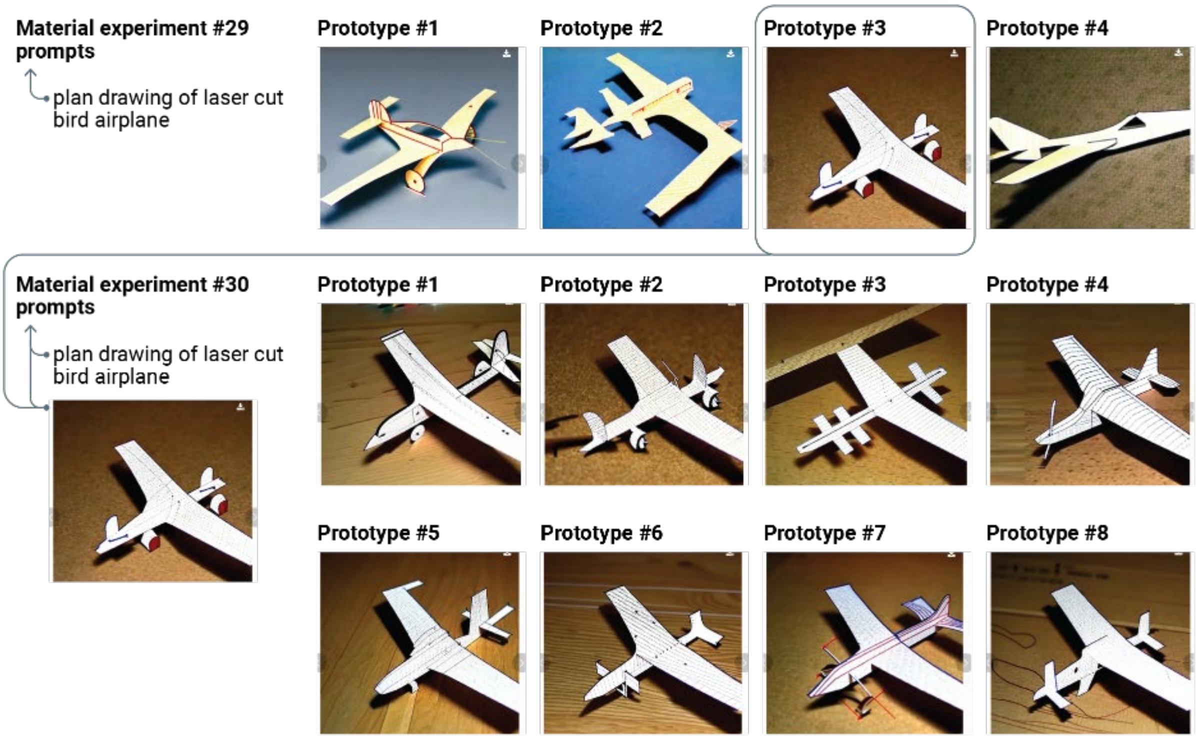


Figure 7: Refining our own prototypes

Example 6: Developing the SD workflow for generating and refining prototypes

In the final stages of our experiments, we combined our learnings described in Example 1 to 5 to develop a start-to-end prototyping workflow (see Figure 8). This prototyping workflow took less than 10 minutes.

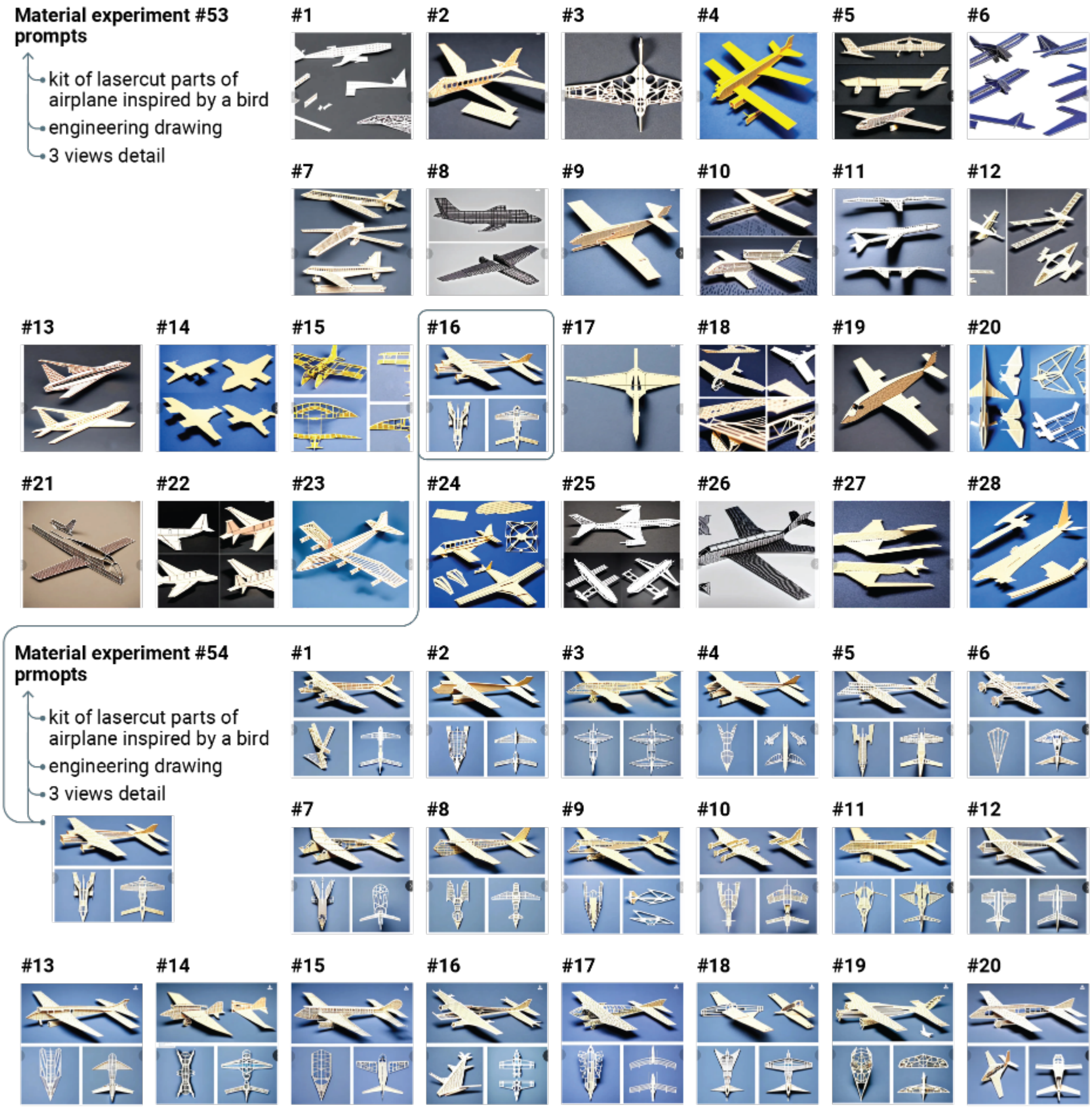


Figure 8: Outcome of SD prototyping workflow

First, we generated 28 prototypes using the following text prompts: "*Kit of laser cut parts of airplane inspired by a bird, engineering drawing, 3 views detail*". These prototypes were plenty and varied, which gave us a large data set to select appropriate images that not only reflected our text prompts but also were suitable to develop as physical prototypes (refer to *Material experiment #53 outcomes* in Figure 8). This process took approximately three minutes.

Of the 28 prototypes, we chose Iteration #16 as we prioritized images that appeared feasible for physical prototyping using a laser cutter. We prioritized this because we expected SD to refine visual prototypes according to our text prompts in subsequent experiments. As expected, the subsequent SD outputs using this specific prototype reflected incremental changes to better reflect the "bird" prompt (refer to *Material experiment #54 outcomes* in

Figure 8). These prototypes exhibited elaborate structural detail while consistently recasting the shape and layout of the primary elements of the airframe. This prototype refinement process took approximately 2 minutes and produced another 20 prototypes. Of the 20 prototypes produced, we developed Iteration #3, #11, #14 and #17 as they had sufficient detail for us to use our design tools to make physical prototypes whilst exploring a variety of outcomes. First, we used Adobe Illustrator to convert the image into a CAD drawing, then used a laser cutter to create the parts in balsa wood and assembled it (see Figure 9).

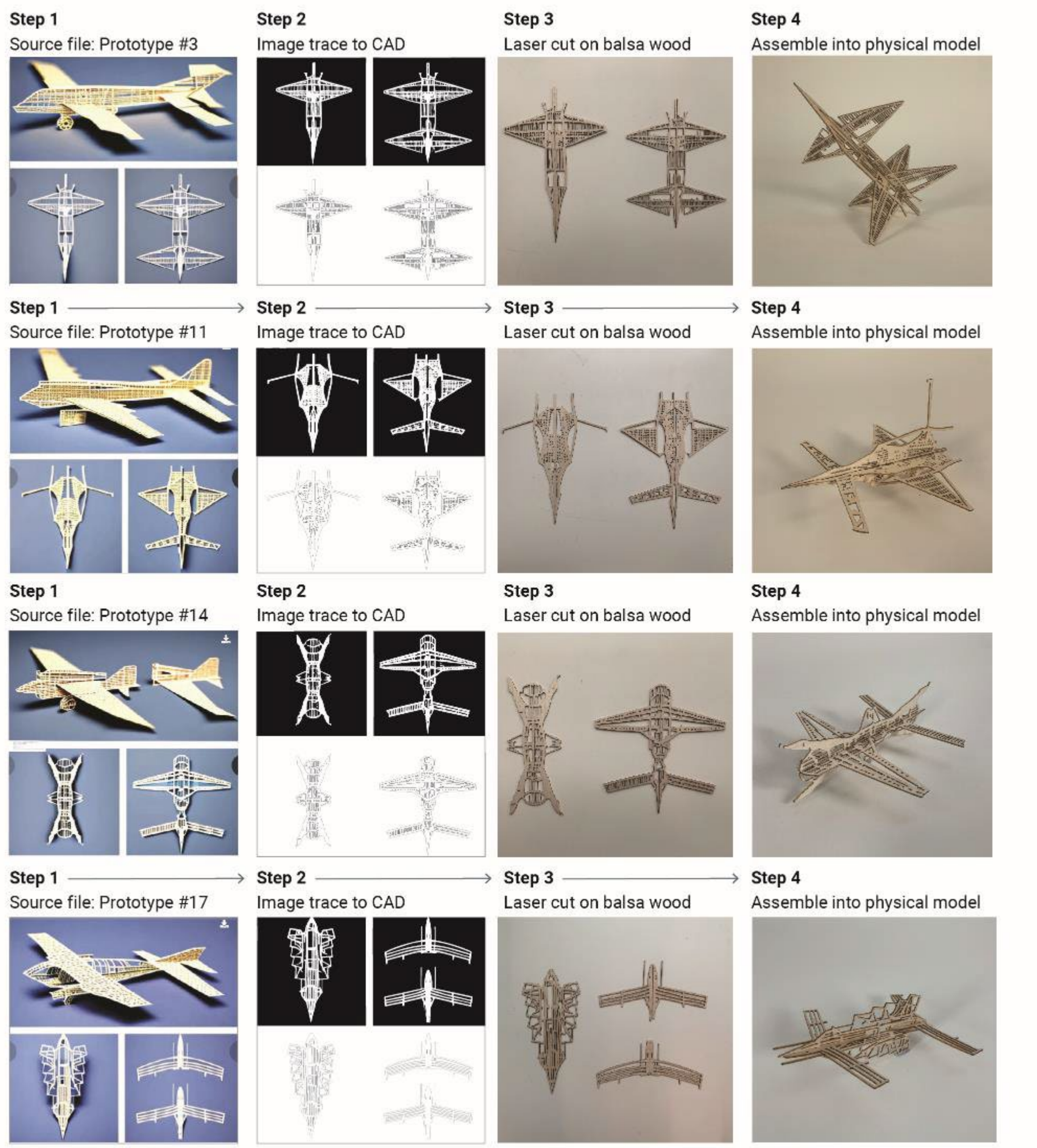


Figure 9: Making the prototype, drawing, laser cutting and assembling

Discussion

This study used software as a design material (Ozenc et al., 2010; Yang, 2018) and by framing design as a reflective conversation with the material (Schön, 1983, 1992; Schön & Bennett, 1996), we explored the role of ML in prototyping aircraft design. Below, we contextualize our work with prior research, discuss the implications of our study on prototyping processes, and propose research opportunities to build on this study of using ML software, such as SD, in prototyping.

Our experiments found three ways where ML can generate aircraft design prototypes. Example 1 showed us that by using keywords to prompt the software, ML will search, analyze, and synthesize publicly available images of the keywords (Murphy, 2012) to produce a variety of outputs. While we expected the outcomes to show certain qualities (i.e. the prompts), the outcomes are unpredictable to a certain degree (Holmquist, 2017). In Example 2, it is this unpredictability that the prototypes "talk back" (i.e., through our reflective conversation with the material) to advance the design. Using a ML software changed how we would typically design and prototype an aircraft design. Our material, which is the intelligence of the ML software (Holmquist, 2017), was able to produce vast amounts of prototypes almost instantly. It is this material property that enabled us to visually assess the feasibility of converting the prototypes into physical models, instead of assessing the feasibility of ideas through prototyping. These experiments demonstrated how working with materials changed the design process (Karana et al., 2019). When we started our experiments, we pursued a range of features and input lengthy prompts into the software. However, once we learnt how the material reacted to our prompts, we changed our ideation to pursue few but specific features. This specificity with the material enabled us to diverge and prototype ideas that were not part of the initial concept. In Example 3, we replaced "bird" with "pelican" and by being specific, had the opportunity to diverge and prototype "hummingbird" and "bat" ideas with the software. As Nimkulrat (2009) demonstrated, material properties can be the source of design concepts. In our case, we used the software to source out a range of concepts, so that we can visually assess and triangulate the prototypes to pick one for further development. Example 3 only showed three forms of animal in combination with three making processes, though we could have easily explored other flying organisms (e.g. owl, dragonfly, beetle etc.) combined with other forms of making processes (e.g. pottery, glass blowing, woodwork).

Our experiments found two ways where ML can refine prototypes. As Dalsgaard (2017) pointed out, materials are instruments of inquiry for designers to explore their design space. Our examples showed how using ML not only can lead to explore new ideas for prototyping, it also can quickly sharpen the inquiry process for designers to investigate certain ideas. While del Campo et al. (2019) referenced images to make their ML software prototype novel designs, we referenced images, as documented in example 4 and 5, to instead refine our prototypes. While Tamke et al. (2017, 2018) used ML to analyze their prototypes so that they can then refine their design, we used ML to learn from its earlier prototypes to refine its subsequent prototypes (i.e. self-referential refinement). Finally, in Luhrs and Tan's (2022) study, they used ML to generate and refine their designs in two different phases. We instead integrated both generating and refining processes and showed in example 6 how they work in a single-phase prototyping workflow. Our experiments and examples shown here supports Yang's (2018) claim that ML is a material and not a tool, for it is based on our tacit knowledge of how the material behaves that we created a prototyping workflow the leverages the ML capabilities.

Our key study limitation was that we were unable to set the pool of visual data that the material (i.e., Stable Diffusion) references from. Hence, though some of the prototypes were ambiguous enough to spark different and more thorough prototyping directions (refer to Example 1 and 2 respectively), there were countless prototypes that failed to 'talk back' and offer us prototyping insights. The second limitation was due to our novice level of prototyping with Stable Diffusion. We only described 16 of the 70 material experiments conducted. The other 54 experiments, though increased our experience with the software, did not provide any significant insights that would improve our prototyping process. Our experiments were also not conducted sequentially. For example, we conducted the experiments of Example 3 after those of Example 5. However, it is important to note that we designed and conducted our workflow for generating and refining prototypes (Example 6) exactly as shown.

Despite these limitations, the study and findings are nonetheless beneficial to further the discussion of how designers can use ML as design materials to inform and accelerate their prototyping process. Building on the findings from this study, we recommend future researchers to consider restricting the pool of visual data that the software references to prototype. Similar to how the image prompt significantly dictated the prototypes, restricting the pool of visual data may provide another approach to refining the prototypes. The broader implication of ML software on the reflective practice theory is that ML may offer researchers opportunities to examine reflection-in-action in greater detail. According to Schön (1983), designers reflect-in-action subconsciously when they are creating a design. Since ML software can almost visualize a design instantly based on their textual inputs, it provides the designer a tangible outcome to evaluate and reflect in the moment of their design process.

For designers intending to integrate Stable Diffusion into their prototyping process, we recommend treating Stable Diffusion as a material instead of a tool. In other words, designers should attempt to understand how the software behaves, like how a designer would approach designing with a material, instead of controlling the software to produce what is needed, like how a designer would employ a tool in their design process. In the context of the aerospace industry, designers are now able to generate numerous prototypes quickly and at scale, enabling them to explore multiple ideas and pathways simultaneously whilst minimizing the typical burden on resources and budget experienced in Aerospace research and development sector.

Conclusion

Machine learning has significant potential to change how we design and prototype. While designers may argue that machine learning is another design tool, we argue that when used as design material, it can help designers produce prototypes to find new ideas and test quickly. As there are few studies that showed how Stable Diffusion, a text-to-image machine learning software, is used in prototyping, this paper provides guidance to designers and researchers on how to do integrate the software into their prototyping process. Our study captured how we used the software as a design material to prototype aircraft designs with little time and financial investments. The first part of the study demonstrates how to use the software in early-stage prototyping to create a variety of prototypes that enable designers to scope out more ideas. The second part of our study demonstrates how to use the software to enhance the visual feasibility of the ideas, which informs the designers when selecting suitable prototypes to make as physical models.

References

Aranda-Muñoz, Á., Florin, U., Yamamoto, Y., Eriksson, Y., & Sandström, K. (2022). Co-Designing with AI in Sight. Proceedings of the Design Society, 2, 101–110. https://doi.org/10.1017/pds.2022.11

As, I., Pal, S., & Basu, P. (2018). Artificial intelligence in architecture: Generating conceptual design via deep learning. International Journal of Architectural Computing, 16(4), 306–327. https://doi.org/10.1177/1478077118800982

Aurora Flight Sciences. (2022, March 17). Aurora's New Lab is a Hub for Innovation in Autonomy. Aurora Careers. https://careers.aurora.aero/2022/03/17/auroras-new-lab-is-a-hub-for-innovation-in-autonomy/

Chen, L., Wang, P., Dong, H., Shi, F., Han, J., Guo, Y., Childs, P. R. N., Xiao, J., & Wu, C. (2019). An artificial intelligence based data-driven approach for design ideation. Journal of Visual Communication and Image Representation, 61, 10–22. https://doi.org/10.1016/j.jvcir.2019.02.009

Choy, J. (2021). Liǎn(脸). https://jannchoy.com/lian.html

Church, G. (2019, February). Learn to fly: Gemma Church looks at modelling and simulation software in the aerospace industry. Scientific Computing World, 164, 24–27.

Dalsgaard, P. (2017). Instruments of Inquiry: Understanding the Nature and Role of Tools in Design. International Journal of Design, 11(1), 21–33.

del Campo, M., Manninger, S., Sanche, M., & Wang, L. (2019). The Church of AI - An examination of architecture in a posthuman design ecology. 767–772. https://doi.org/10.52842/conf.caadria.2019.2.767

Dove, G., Halskov, K., Forlizzi, J., & Zimmerman, J. (2017). UX Design Innovation: Challenges for Working with Machine Learning as a Design Material. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, 278–288. https://doi.org/10.1145/3025453.3025739

Dreith, B. (2022, November 16). How AI software will change architecture and design. Dezeen. https://www.dezeen.com/2022/11/16/ai-design-architecture-product/

d.School. (2018). I Love Algorithms. Stanford d.School. https://dschool.stanford.edu/resources/i-love-algorithms

Florian, M.-C. (2022, August 15). Can Artificial Intelligence Systems like DALL-E or Midjourney Perform Creative Tasks? ArchDaily. https://www.archdaily.com/987228/can-artificial-intelligence-systems-like-dall-e-or-midjourney-perform-creative-tasks

Futurice. (2020). The Intelligence Augmentation Design Toolkit. Futurice. https://iadesignkit.com/ia-design-kit

Hille, K. (2023, February 9). NASA Turns to AI to Design Mission Hardware [Text]. NASA. http://www.nasa.gov/feature/goddard/2023/nasa-turns-to-ai-to-design-mission-hardware

Holmquist, L. E. (2017). Intelligence on tap: Artificial intelligence as a new design material. Interactions, 24(4), 28–33. https://doi.org/10.1145/3085571

Hyperganic Group. (2021). Hyperganic Core 3. Hyperganic. https://www.hyperganic.com

Karana, E., Nimkulrat, N., Giaccardi, E., Niedderer, K., & Fan, J.-N. (2019). Experiential Knowledge and Emerging Materials. 13(2).

Khan, R. (2022, December 1). Top 10 of 2022—A new wave of AI-generated design. Designboom | Architecture & Design Magazine. https://www.designboom.com/design/top-10-readers-submissions-2022-new-wave-surreal-ai-generated-design-12-01-2022/

Koch, J. (2017). Design implications for designing with a collaborative AI. AAAI Spring Symposium - Technical Report, SS-17-01-, 415–418.

Luhrs, M., & Tan, L. (2022, December 1). Incorporating Artificial Intelligence Generated Visualisations in the Architectural Design Process [Conference Presentation]. Architecture, Media, Politics and Society: Representing Pasts Visioning Futures Conference, Online. https://amps-research.com/event/visioning/schedule/digitality-architecture-urban-space/incorporating-artificial-intelligence-generated-visualisations-in-the-architectural-design-process/

Main, A., & Grierson, M. (2020). Guru, Partner, or Pencil Sharpener? Understanding Designers' Attitudes Towards Intelligent Creativity Support Tools (arXiv:2007.04848). arXiv. http://arxiv.org/abs/2007.04848

Malsattar, N., Kihara, T., & Giaccardi, E. (2019). Designing and Prototyping from the Perspective of AI in the Wild. Proceedings of the 2019 on Designing Interactive Systems Conference, 1083–1088. https://doi.org/10.1145/3322276.3322351

Mateescu, A., & Elish, M. (2019). AI in context: The labor of integrating new technologies (United States of America) [Report]. Data & Society Research Institute. https://apo.org.au/node/217456

Murphy, K. P. (2012). Machine Learning: A Probabilistic Perspective. MIT Press.

Nimkulrat, N. (2009). Paperness: Expressive material in textile art from an artist's viewpoint. University of Art and Design Helsinki.

Ostrower, J. (2015, April 2). At Boeing, Innovation Means Small Steps, Not Giant Leaps. Wall Street Journal. https://www.wsj.com/articles/at-boeing-innovation-means-small-steps-not-giant-leaps-1428016900

Ozenc, F. K., Kim, M., Zimmerman, J., Oney, S., & Myers, B. (2010). How to support designers in getting hold of the immaterial material of software. Proceedings of the 28th International Conference on Human Factors in Computing Systems - CHI '10, 2513. https://doi.org/10.1145/1753326.1753707

Schön, D. A. (1983). The Reflective Practitioner: How Professionals Think in Action. Basic Books, Inc.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. Knowledge-Based Systems, 5(1), 3–14. https://doi.org/10.1016/0950-7051(92)90020-G

Schön, D. A., & Bennett, J. (1996). Reflective conversation with materials. In T. W. Winograd (Ed.), Bringing design to software (pp. 171–189). ACM Press.

Sidewalk Labs. (2022). Delve, A Real Estate Generative Design Product. Sidewalk Labs. https://www.sidewalklabs.com/products/delve

SPAN. (2020). Peaches & Plums. SPAN. https://span-arch.org/peaches-plums/

Stability.ai. (2022). Stable Diffusion Public Release. Stability.Ai. https://stability.ai/blog/stable-diffusion-public-release

STARCK. (2020, January 24). A.I. - Introducing the first chair created with artificial intelligence. STARCK Site Web Officiel. https://www.starck.com/a-i-introducing-the-first-chair-created-with-artificial-intelligence-p3801

Tamke, M., Nicholas, P., & Zwierzycki, M. (2018). Machine learning for architectural design: Practices and infrastructure. International Journal of Architectural Computing, 16(2), 123–143. https://doi.org/10.1177/1478077118778580

Tamke, M., Zwierzycki, M., Deleuran, A. H., Baranovskaya, Y. S., Tinning, I. F., & Thomse, M. R. (2017). Lace Wall—Extending design intuition through machine learning. In A. Menges, B. Sheil, R. Glynn, & M. Skavara, Fabricate 2017 (pp. 98–105). UCL Press. https://doi.org/10.2307/j.ctt1n7qkg7

Tan, L. (2021). From Reflective Practitioner to Learning Professionals: The role of reflecting and learning in architecture teams [Swinburne University of Technology]. https://researchbank.swinburne.edu.au/items/e20941a5-21e3-4bfb-ab32-2a280e8b2823/1/

Tan, L., Kocsis, A., & Burry, J. (2023). Advancing Donald Schön's Reflective Practitioner: Where to next? Design Issues, 23(3), 3–18. https://doi.org/10.1162/desi_a_00722

Try Tiggers. (2020). Machine Learning Deck. Triggers. https://www.trytriggers.com/shop-triggers-tools/machine-learning-deck

Wilkinson, S., Bradbury, G., & Hanna, S. (2014). Approximating Urban Wind Interference. Proceedings of the Symposium on Simulation for Architecture & Urban Design (SimAUD '14), 8.

Wu, Z., Ji, D., Yu, K., Zeng, X., Wu, D., & Shidujaman, M. (2021). AI Creativity and the Human-AI Co-creation Model. In M. Kurosu (Ed.), Human-Computer Interaction. Theory, Methods and Tools (Vol. 12762, pp. 171–190). Springer International Publishing. https://doi.org/10.1007/978-3-030-78462-1_13

Yang, Q. (2018). Machine Learning as a UX Design Material: How Can We Imagine Beyond Automation, Recommenders, and Reminders? AAAI Spring Symposium Series, 467–472. https://aaai.org/ocs/index.php/SSS/SSS18/paper/view/17471

Zimmer, J. (2023, January 26). AI in the Air: How Aerospace Engineering is Getting Smarter. Engineering.Com. https://www.engineering.com/story/ai-in-the-air-how-aerospace-engineering-is-getting-smarter

Linus Tan

Dr. Linus Tan is an architectural designer, lecturer and researcher in the School of Design and Architecture at Swinburne University of Technology, Australia.
He researches how designers think, act, and learn (design cognition, behavior and professional learning), and how using generative AI software changes how

designers and design teams think, act, and learn. He is also a research member of Centre for Design Innovation and the research lead (design) in Aerostructures Innovation Research Hub at Swinburne University, where he applies his research by helping designers innovate their design processes with the use of AI tools.

Thom Luke

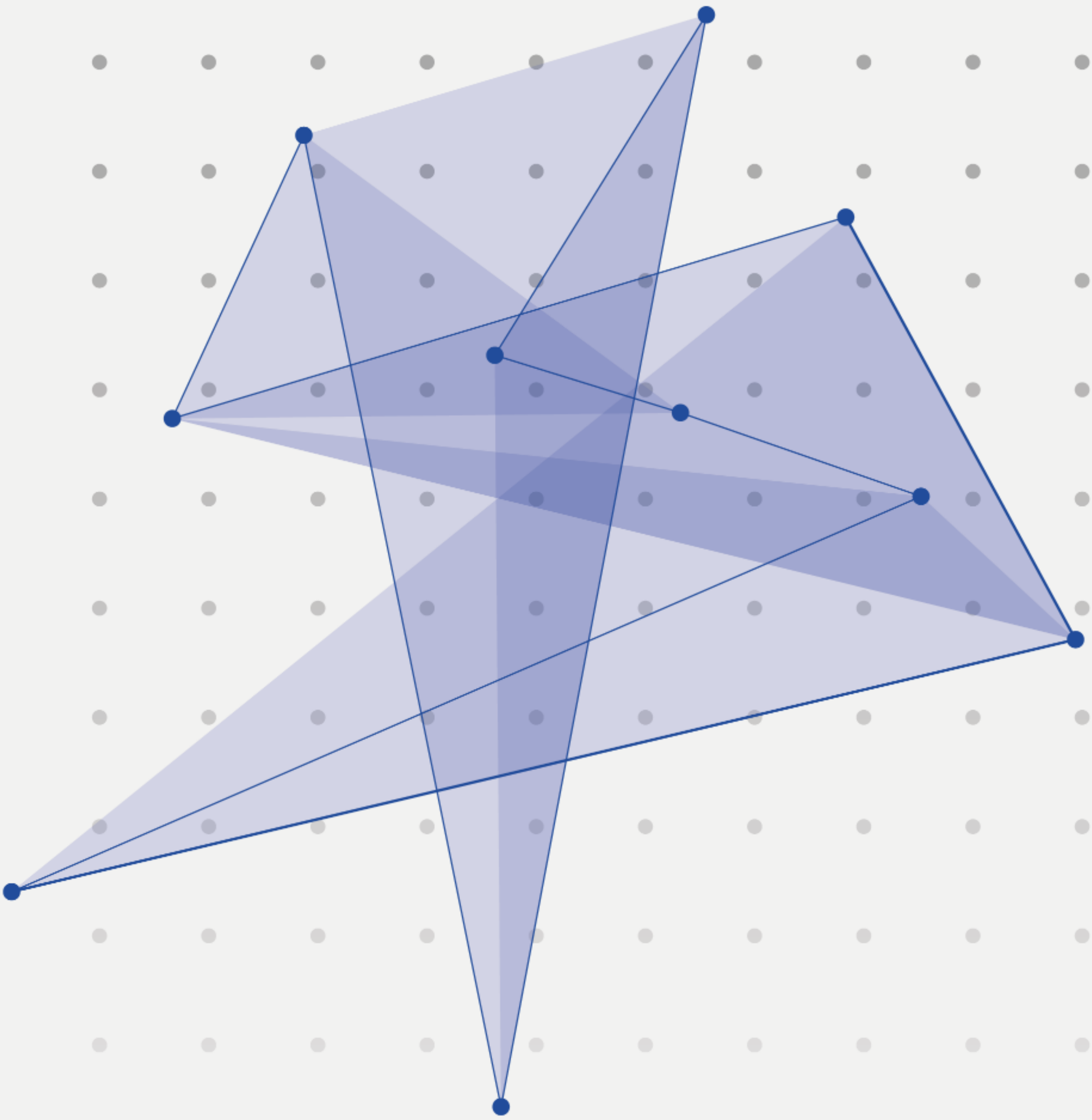
Thom Luke is an Industrial Designer and PhD candidate at Swinburne University of Technology through the AIRHUB and the School of Design and Architecture. Thom is an experienced product designer, having founded his consultancy "Threshold Design" in 2011 (http://www.thresholdesign.com.au/). With a passion for design, aviation, and innovation, Thom is exploring the capability of emergent ML and AI models and their role in progressing design and design process. A champion of disruptive thinking and disruptive technology, Thom looks to produce research that is both exciting and valuable to the greater academic community.

Adriano di Pietro

Dr. Adriano Di Pietro has over 15 years of international experience in advanced technology development both in aerospace and the automotive industry. As the founding Director of the AIR Hub, he has assembled a team of over 50 aerospace-focused staff and post-graduate students and built an international partnership network undertaking deep tech-focused applied research.

Anita Kocsis

Prof. Anita Kocsis is the Director of Design Factory Melbourne, Swinburne University's interdisciplinary innovation lab. Anita is a champion of the lab to create the conditions for innovation by working on challenges beyond the scope of a single discipline or research practice. Kocsis spans academia and enterprise operating in complex multi-stakeholder environments including a start-up in the museum sector at EPFL Lausanne, Principal Innovation Fellow at the Australian Nuclear Scientific Organisation and vice chair of the Experience Research Society.



Track 11: Interaction, Data and AI 2

- The eloquent void: strangeness in data physicalization about loneliness
- The Artificial Lyricist: Prototyping an Interactive Opera for Humans and Machines
- Graft-games: Experiential prototyping for the exploration of crossovers between craft and gaming
- Idiotic Agents: Exploring more open-ended and creative interactions between humans and Intelligent Personal Assistants in the home

The eloquent void: strangeness in data physicalization about loneliness

Guedes Mesquita, Rebeca, Hochschule Anhalt, Germany
Thoring, Katja, Technical University of Munich, Germany

Abstract

Data is central to countless recent discussions, but the most recurrent approach is still graphic visualizations. As new technologies and platforms have allegedly democratized and expanded access to information, these visual charts are likely saturating our cognitive efforts. Data physicalization – an emerging research area that conveys data through objects – attempts to present information more efficiently and memorably. Due to its embodiment potential, the approach encourages and invites people to reflect on their social and cultural surroundings while engaging their bodies and imagination. Acknowledging that, the research presented in this paper tries to tackle the impacts of material-weight strangeness in data physicalization by evaluating four experiments conducted with 41 international participants. It compares the performance of physicalizations and visualizations to foster emotional engagement and awareness regarding abstract data. Since the COVID-19 pandemic restrictions significantly increased self-reported chronic loneliness across all the EU macro-regions, initiating meaningful discussions around the topic became our motivation.
The results suggest the physical interactions enhanced the selected dataset memorability rather than the virtual ones. On the other hand, the strangeness provoked by material-weight illusion treatments either improved or jeopardized the physicalization's efficiency. Furthermore, based on the research findings, design is likely to be an appealing tool for enhancing engagement in data communication.

Data Physicalization; Strangeness; Memorability; Efficiency; Lonelines

Information is pervasive in society nowadays. New technologies and digital mediums have escalated and amplified access to data. But, as the competition for attention increases, emergent communication approaches attempt to present information more efficiently and memorably. As unappealing visualizations might cause outreach losses to scientific knowledge, the current design project explores preferred possibilities in data communication.

Data physicalization – an emerging field in which artifact properties like geometry and material are means for data encoding – is the focus of this study. Since it “uses physical data representations to help people explore and communicate” (Jansen et al., 2015, p.3227), the embodiment derived from one's interaction with these tangible pieces of information is “based on the assumption that abstract information can be [...] touched, explored, carried or even possessed.” (Zhao & Moere, 2008, p.343)

The COVID-19 outbreak unleashed struggles that might damage our well-being long after the pandemic subsides. Social restrictions and the overexploitation of digital platforms became urgent and a matter of civic duty. The relevance and benefits of these adaptations are unquestionable. However, it is also prominent to account for the ravages they triggered in our mental health and productivity. Chronic loneliness is one of them, and it significantly increased across the European Union macro-regions between 2016 and 2020.

Aiming to leverage conversations about loneliness, we tried to transform data decoding into a more entertaining and meaningful experience by intentionally designing material-weight strangeness in data physicalization. Due to that, our Research Question is: How to foster emotional engagement and awareness regarding abstract data? While the Design Question is: How can strangeness in data physicalization enhance efficiency and memorability?

Since Design has its own ways of knowing (Cross, 1982), the current work counts with two distinct milestones. The first is design-led with an expert mindset (Sanders, 2008), where data objects are the outcome of systematic conceptualizations and prototypes. The second is research-led with a participatory mindset, where 41 international volunteers engaged with the crafted artifacts during four different comparative experiments. Overall, the research analysis focuses on the data collected through two surveys and observations following these experiments. The main envisioned outcome was to compare the efficiency and memorability results between physicalization and graphic visualization.

Theoretical Background

Design is ontological (Escobar, 2018) and entails “not only a valid but also a valuable epistemological stance.” (Findeli, 2010, p.294). The existential nature of the field implies non-consensual definitions, but despite that, the designerly ways of knowing and doing (Cross, 1982) definitely help us make better-informed decisions everywhere. Having that in mind, the following section outlines relevant theoretical aspects regarding the overlap of design with data physicalization, engagement, experience, and strangeness.

Data Physicalization and Engagement

Visual conventions to data literacy have been engendered in Western educational systems since their early stages in the first half of the 19th century (Friendly, 2006). Due to that, it is unlikely that one comes to adulthood without previous contact with data visualization. Its value to learning processes and knowledge spreading is indisputable, but its omnipresence might be “saturating the visual senses and the cognitive efforts of the lay masses.” (Zhao & Moere, 2008, p. 343) Data physicalization can be traced centuries back as well (Dumičić et al., 2022). It does not have such limiting or pragmatic conventions, though.

Due to its perceived novelty, several studies try to underline best practices to design efficient and memorable data physicalizations. Sosa et al. (2018), for instance, recommend (1) treating data as a new type of material, (2) designing for access and (re)interpretation of the data embedded in the object, (3) designing for cognitive and emotional engagement, and (4) designing to empower people to use the data to rethink and challenge the status quo.

Those pieces of advice acknowledge that the touch of an object – and the inherent exploratory movements invested in the process – reveal numerous physical properties and features of its surface, like roughness, compliance, and stiffness. (Wang et al., 2019) These aspects, in turn, enable every encounter with a data artifact to become “a critical inquiry into materiality, context, and the process of making." (Offenhuber, 2019, p.4)

Embodiment and Metaphorical Distances

Accounting for those physical engagement benefits, Zhao & Moere (2008) present a model in which data embodiment is measured according to the distance between metaphor/data and metaphor/reality. Because both authors believe the primary function of metaphors is conceiving unfamiliar domains into familiar ones, their proposed embodiment model relies on the following assumptions:

> *(1) Data sculpture is a system of physical representation and abstract data coupled by a relationship called embodiment. (2) Metaphor is a contributing factor to embodiment and can be gauged by metaphorical distances from the data and reality. (3) Different modes of embodiment determined by different metaphorical distances in data sculpture can affect the informative value. (p.347)*

Their model thus identifies three main categories of metaphorical distances: 'far from data but close to reality', 'close to both data and reality', and 'far from both data and reality'. When conveying data on such an abstract and emotional concept as loneliness, a metaphoric approach far from data and reality seems to be the most feasible because "directly identifiable or intuitive metaphors are absent." (Zhao & Moere, 2008, p.347)

Conceptual Expectancy and Weight-Illusion

Besides embodiment, another relevant outcome of tangible interactions is the understanding that an artifact's perceived physical weight is subjected to several distinct factors, such as size, material, mass distribution, and shape. According to Saccone et al. (2019), there is "a complex process by which the brain considers multiple types of visual and somatosensory information to make sense of an object's weight." (p.1195) This process is known as 'conceptual expectancy' and its accounts are based on "studies that manipulate expectations of object weight." (Saccone, 2019, p.1196)

For example, Buckingham & Goodale (2009) describe a material-weight illusion experiment where participants lift three equally sized and massed blocks that appear out of different materials – aluminum, oak wood, and polystyrene. Their findings suggest the participants' material expectations consistently influenced their perception of the blocks' weights, leading them to consider the one out of polystyrene the heaviest.

Stusak et al. (2016) in the "If Your Mind Can Grasp It, Your Hands Will Help" article, on the other hand, describes a memorability study comparing 2D and 3D visualizations. The authors designed wooden blocks bar charts and evaluated their remembrance in comparison to a paper-based visualization of the same dataset. Among the findings, they wrote:

> *"We could not find an influence of the physical factor weight, possibly because the weight of objects in our studies totally conforms with typical expectations. Further studies could try to investigate whether breaking these expectations could generate additional benefits". (p.98)*

Considering these authors' suggestions and findings, the current study tries to mitigate potential research gaps while exploring a more holistic and broad approach to data communication. Moreover, due to its hypothetical potential to stimulate feelings of strangeness, the material-weight phenomenon mentioned might allow us to glimpse the relevance of embodiment on abstract data efficiency and memorability.

Experience and Strangeness

Design is intentionally transforming resources according to a functional end. In this sense, "everything instrumental to human existence and well-being was, in its prototype form, designed by a human – a designer."(Richardson, 2011, p.9) Although design "has been traditionally placed under the domain of applied arts, rather than science – where research dominates" (Muratovski, 2016, p.10), the area usually functions as a bridge between both epistemological fields.

When the 'functional end' is data communication, the 'resource' to be 'transformed' by design might be the learning experience itself. Kolb & Kolb (2005) postulate that grasping and transforming experiences result in knowledge. They believe learning occurs through "the equilibration of the dialectic processes of assimilating new experiences into existing concepts and accommodating existing concepts in new experiences" (Kolb & Kolb, 2005, p.194). Dewey (2005), in turn, remarks only 'reason' is insufficient to grasp a self-contained assurance. It "must fall back upon imagination – upon the embodiment of ideas [...]" (p.34), suggesting design may assist in communicating data through engaging experiences.

In parallel, Dautrey & Quinz (2015) attest that, through strangeness, designers have "outlined another way forward, by moving away from functionality – but without really moving away – and by exploring the atypical, subversive, and unexpected dimension of functionality." (p.349) In general, every tangible artifact sparkles pre-established mental images or representations that allow us to predict its affordance. But contradicting these expectations does not necessarily imply confusion or unpleasantness. Depending on the intentions, physical (or virtual) unpredicted interactions can attach us more to reality and the moment instead.

> *This is because the strange is both what separates us from the world (the experience of the strange being the experience of an alterity that stops us from acting within it according to established norms) and what plunges us into it (from the point of view that this experience merely separates us from the fake world in which we live in). (Dautrey & Quinz, 2015, p.366)*

Every agent (a user) in a relationship with an artifact (tangible or not) or the environment evokes an experience. (Garrett, 2010) When the dynamic or interaction is complete, there is participation and communication. (Dewey, 2005) Underlying these processes and notions is compulsory for this project, as verifying the impacts of material-weight illusions (strangeness) on data efficiency and memorability could be relevant for leveraging discussions regarding loneliness. After all, "physical artifacts are laden with social and cultural meanings that designers can leverage to craft particular avenues of open-ended interpretation." (Howell et al., 2018, p.7) Otherwise, what better approach to emotional engagement and awareness than embodied experiences?

Study Settings

Schön (1987) implies the most suitable method for a particular design project varies according to its demands. In agreement with that, the current work entailed distinct methodologies to achieve two main milestones. The first – Designing –, consists of action research carried out through repetitive divergence/convergence and analysis/synthesis processes. (Dubberly, 2004) Its goal was to craft suitable data physicalizations and visualizations to experiment with in the subsequent stage – Evaluating.

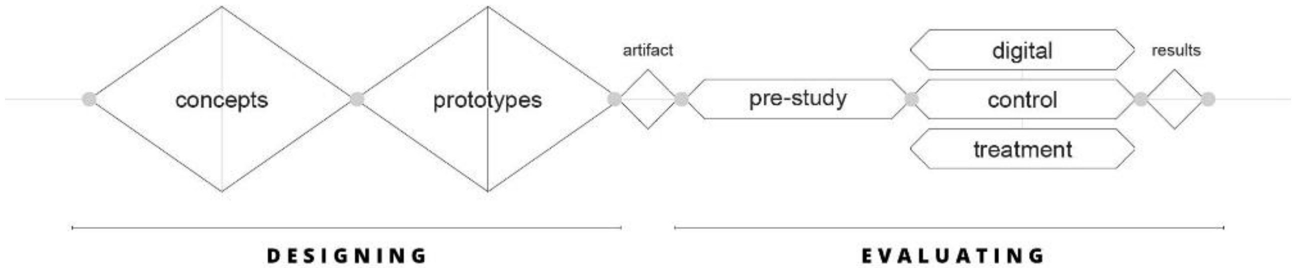


Figure 1: Overview of the current design research milestones.

Designing

The methodological model applied to this primary milestone was conceived by Bela Banathy in 1996 and then popularized under the term ‘double diamond.’ For this paper, the first ‘diamond’ refers to concepts and explorations, introducing the foundational ideas, references, and datasets. The second, on the other hand, approaches the prototypes and implementations, their most meaningful findings, and the limitations faced.

Concepts and Explorations

The COVID-19 pandemic triggered the arousal of several struggles worldwide. Self-reported chronic loneliness is one of them. Panksepp (2004) posits that “social bonding ultimately involves the ability [...] to experience separation distress when isolated from social support systems and to experience neurochemically mediated comfort when social contacts are reestablished.” (p.274) This means that all of us, in more or less intention, experience physical and emotional discomfort when deprived of social contact.

From a public policy perspective, however, “it is chronic loneliness that entails the most detrimental consequences, requiring intervention and appropriate health and social care policies.” (Baarck et al., 2021, p.10) Exactly because persistent loneliness is the one that “leaves a mark via stress hormones, immune function and cardiovascular function with a cumulative effect that means being lonely or not is equivalent in impact to being a smoker or non-smoker.” (Griffin, 2010, p.4)

In addition, the perpetuation of Western structural features is likely to aggravate the loneliness scenario. Capitalism, neoliberalism, and meritocracy increase competition and individualism. In return, all the overwhelming socially isolated individuals impact the social structure. Burdening the healthcare system and having work productivity compromised, the affected population has a substantial adverse economic influence.

Understanding the topic's relevance, we started by choosing three distinct quantitative datasets from the “Loneliness in the EU” report (Baarck et al., 2021). For each, one physicalization concept was developed following premises from the multiple literature review references. The most appropriate was the one concerning the loneliness increase among all the European Union macro-regions during the COVID-19 pandemic, as the data itself was already surprising.

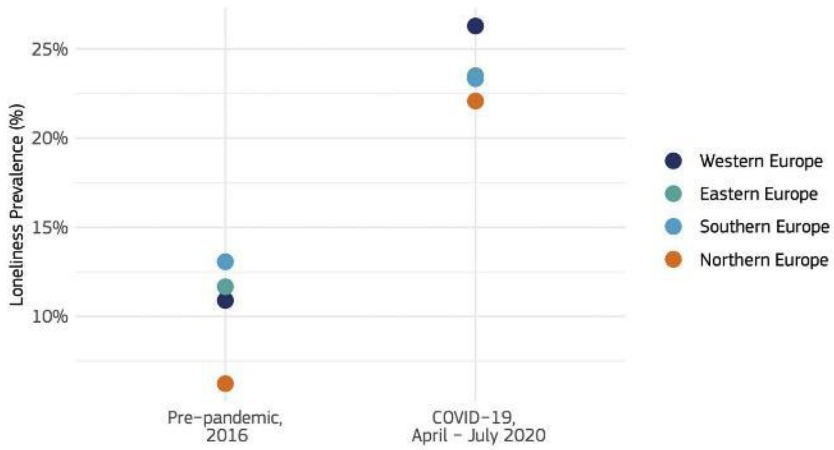


Figure 2: Loneliness by macro-region original dataset. Data sources: Eurofound, 2016 EQLS and 2020 LWC surveys; The figure displays, by EU macro-region and time period, the share of individuals who felt lonely more than half of the time over the two weeks preceding the interview. (Baarck et al., 2021, p.30)

According to Baarck et al. (2021), we “would expect the effect of social distancing to be more severe in countries or macro-regions where people are more tactile [...]. In that sense, the suffering from the lack of contacts should be higher in southern Europe than in northern Europe.” (p.31) However, the dataset firmly contradicts that assumption.

After conducting six semi-structured interviews to gather relevant insights about the subjects’ understanding of loneliness, their answers were synthesized into a list with the most relevant keywords. Sixteen subjects voted on one word that most resonated with their idea of loneliness. Then, the three most voted ones – Disconnection, Emptiness, and Inaccessibility – guided the exploration of new concepts. Each of them entailed aspects that could potentially result in an attractive physicalization. But, at this point, it was decided to: (1) create a physical 3D puzzle that conveys the data, (2) have this object metaphorically symbolize loneliness, and (3) provide a playful strangeness for the user.

Sosa et al. (2018) consider two methods for designing a data object: (1) from data to object, and (2) from object to data. The former was adequate for this project because the dataset was selected previous to the object. The authors suggest that “features derived from the data can distort the object – break expected symmetry, proportion, or scale – while metaphors and symbols can be used to transmit meaning.” (p.1690)

Accounting for those guidelines, philosophy and Greek mythology highly assisted in the physicalization ideation. In the Sisyphus’ Myth, for instance, the hero was condemned to endlessly push a boulder up a mountain alone, only to see it roll down again afterward. This story can relate to the loneliness' burden and heaviness when one realizes relationships are, ultimately, a hopeless and infinity labor.

Prototypes and Implementations

Once the most compelling concepts and metaphors were defined, the prototyping cycles began and focused on refining the physicalization. (Muratovski, 2005) Four different combinations of data encoding were tested with six users during this stage. Its ultimate purpose was to underline how to (1) improve the subject-object interaction, (2) explain the metaphors behind the design decisions, and (3) secure the correct reading of the dataset.

Considering the insights gathered previously, the final object became a turning-board/card game that functioned like a puzzle/enigma and revealed the data encoded during the gameplay. The ultimate goal was to guess the effect (loneliness) measured between 2016 and 2020 in the EU macro-regions. Additionally, the artifact symbolized the disconnection concept by the necessary pieces assembling for proper data decoding. The hollow and transparent parts out of resin represented emptiness, while the unreachable materials inside the pyramid's upper parts referred to inaccessibility.

The strangeness was addressed by those inner materials and their intentionally controlled weights. The upper parts patterns printed on carton paper ensured correct assembling and abstractly represented the EU macro-regions. Finally, the sharp and abstract shapes spoke about the danger and discomfort inherent to loneliness. In “The Lonely Society?” article, Griffin (2010) posits the connection between “anger, sadness, depression[...] and pessimism” (p.15) to loneliness, which also justifies the greyscale color decision.

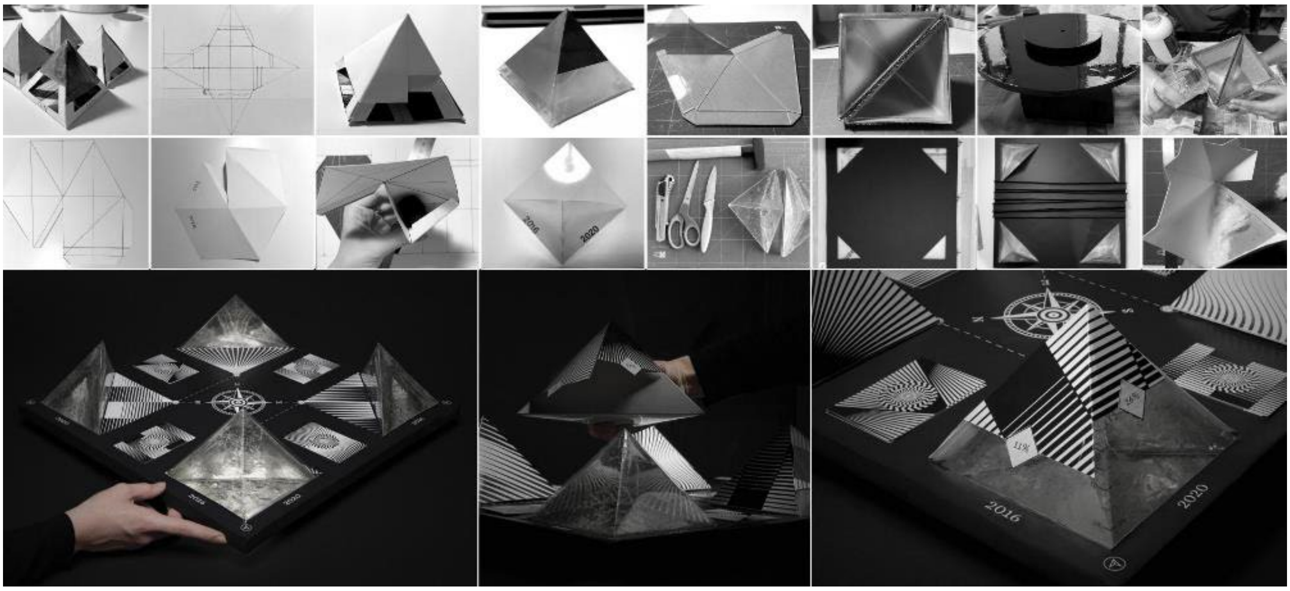


Figure 3: Prototypes and final implementation of the physicalization conveying the loneliness by macro-region data. The gameplay guided the users' interaction with the physicalization through instructions and hints given by the cards placed on the board. The data was revealed gradually according to the upper parts assembling, and the goal was to guess the effect measured (loneliness) by the final puzzle/artifact when completely assembled.

Evaluating

The project's second milestone aimed to compare data physicalization to graphic visualization. It investigated the following hypothesis: Strangeness regarding an object's material-weight expectations improves the physicalizations' efficiency and memorability. Hence, four experiments were designed and conducted with 41 international participants aged between 22 and 65. The sample was distributed per experiment as follows: (E1) Pre-Study: 12, (E2) Digital: 14, (E3) Control: 7, and (E4) Treatment: 8 participants.

The original research proposal predicted only three experiments. The first would count with distinct weight-material illusions linked to the ‘loneliness increase’ parameter: (1) Southern: 10% ≈ 45g, (2) Eastern: 11% ≈ 90g, (3) Western: 15% ≈ 270g, and (4) Northern: 16% ≈ 315g. The second would be conducted through data visualizations but with all the physicalized graphics and storytelling elements translated into digital mediums. And the third would be the control group without treatment. However, during the first experiment, the necessity for a fourth one arose.

After collecting the memorability results from the first experiment (E1), we noticed the responses to a particular task diverged severely. There were a few possible causes for this unpredictable divergence, so we decided to consider it a pre-study to identify and mitigate emergent problems. The research proceeded with the new treatment connected to the parameter ‘2020 loneliness percentage’ instead of the 'loneliness increase.' Therefore, the upper parts' weights became: (1) Southern: 23% ≈ 150g, (2) Eastern: 23% ≈ 150g, (3) Western: 26% ≈ 525g, and (4) Northern: 22% ≈ 25g. This decision increased the research rigor and allowed us to glimpse the effects of material-weight strangeness on the dataset information recognition.

Methodology

According to Muratovski (2016), “[t]here is always a benefit in using multiple sources of evidence when conducting research. This process of cross-referencing your research is called triangulation. This way of working can help you establish credible, valid, and reliable research practice.” (p.39) Recognizing those advantages, the current research involved the triangulation of surveys and observations. The quantitative data were analyzed via statistics, while the qualitative ones were either template or open-coded (Blair, 2015).

Sample

The sample was composed mainly of design and architecture students, with few exceptions. They were all invited to schedule appointments via direct messages on social media or posts on the HSA Design Platform (Icom) one week before the starting date. We controlled the room environment and provided snacks as compensation for the physical interactions but not for the virtual ones. Regarding the latter, since some subjects were not proficient in Zoom and Miro, the complete procedure for those meetings lasted almost 25% longer than the former ones. We did not warn the subjects regarding the memorability test, and they were all invited to the second survey via email, which offered a Newsletter as a reward.

Surveys

The surveys consisted of two questionnaires with open and close-ended questions. The first – Efficiency – was responded to in loco after the interactions with the physicalization or visualization. The second questionnaire – Memorability – was forwarded to the subjects via email one week after the experiment. As the name suggests, the former's focus was to evaluate the efficiency in conveying the original dataset. For the latter, the intention was to measure the information recognition. Some criteria were previously stipulated, though.

Efficiency

Inspired by comparative studies (Jansen et al., 2013), the performance measurement was based on quickness (time on task) and accuracy (error rate). The efficiency calculation, in turn, was according to the mathematical 'r = O/I' formula. Where 'r' was the ratio of relevant 'Output' (O) to total 'Input' (I). The output 'O' for these experiments was the accuracy, while the input 'I' was the participants' quickness to respond to three tasks. Those efficiency tasks were divided into three categories: (1) Compare task, (2) Order task, and (3) Range task. The sum of correct answers to these queries represented the overall experiment accuracy.

Memorability

Similarly to Stusak et al. (2015), the 'Memorability' questionnaire asked the same task questions after one week. The new answers were compared to the previous ones. If they matched, it was considered a sign of recognition. Otherwise, if the responses did not agree, the result was non-remembrance. Two new questions about the data were also included in this last survey: (4) Extreme Values and (5) Facts. If the answers to these queries were accurate, they indicated data memorability.

Observations

To collect the data regarding quickness (the time consumed as input 'I'), we documented the seconds every participant needed to respond to each task of the 'Efficiency' questionnaire. We also checked whether the participants correctly assembled the macro-regions upper parts during each virtual and physical experiment. These observations provided insights into the patterns' efficiency and led to intriguing findings afterward. Furthermore, this method assisted in understanding the overall experience and contributed to mitigating problems.

Analysis and Synthesis

Overall, there were four principal sources of data to analyze: (1) surveys' close-ended questions, (2) surveys' open-ended questions, (3) gameplay open-ended questions, and (4) observations' transcriptions and annotations. Thus, a few methods supported the quantitative and qualitative analysis of the present research.

Quantitative

With the assistance of the Stata 13.1 software, it was possible to calculate the measurements for efficiency, memorability, and awareness. Besides, the statistics also helped identify the design decisions that most positively got the participants' attention. Well as the ones that could be improved. Furthermore, the quantitative results led to unexpected insights regarding gender and its connection to the experiments' awareness evaluation.

Qualitative

Initially, we revisited the Research and Design Questions and defined ten codes (C) to analyze the qualitative data gathered through the surveys. They were: (C1) Narrative - Gameplay or Metaphor, (C2) Graphics - Patterns, Colors, or Typographies, (C3) Space - Environment, (C4) Dataset, (C5) Geometry - Shapes or Sizes, (C6) Material - Textures or Weight, (C7) Efficiency, (C8) Memorability, (C9) Awareness, and (C10) Emotion - Strangeness and Others. These codes assisted in clustering the user feedback and led us to the most relevant findings.

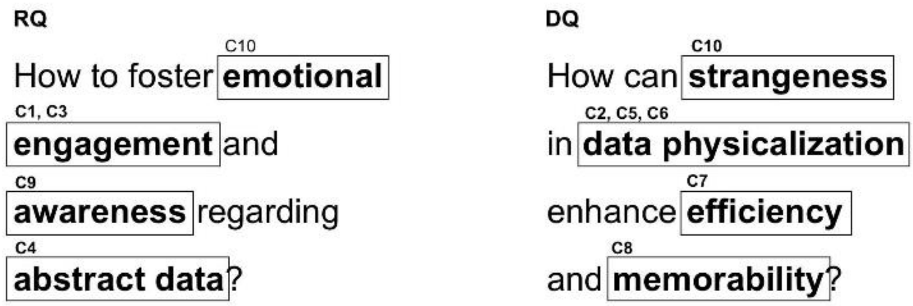


Figure 4: Top-down generated codes to support the qualitative analysis.

The gameplay narrative, in turn, involved several open-ended questions posteriorly analyzed. Among the questions presented in the game cards, three entailed close attention: (Q1) How could 'hopeless labor' resonate with your life experience; (Q2) What could be a social trigger for [mental-health] conditions; and (Q3) Which mental/emotional struggle could be the effect measured in the current dataset? These queries generated the codes that assisted us in tackling the Research Question.

Results

The statistical analysis suggests all the physicalizations performed better in memorability than the graphic visualizations. But, as the general performances from the Pre-Study (E1) and Treatment (E4) significantly diverged, the strangeness' impacts on them remain inconclusive. This assumption is reinforced by the gameplay and surveys qualitative analysis, which suggest the material-weight treatments were either not consciously perceived or understood as directly connected to the dataset. Therefore, further investigations are compulsory to address the strangeness' contribution to data efficiency and memorability.

The Digital experiment (E2) had the highest accuracy performance with almost 93% correctness. This result is not surprising, as it is probably related to the sample's familiarity with data visualization. On the other hand, the Control's (E3) artifact and its absence of weight treatment led this experiment's participants to the worst accuracy and efficiency performances. This constatation corroborates the assumption that the Pre-Study's (E1) treatment probably improved accuracy. However, since the subjects from E3 performed better in memorability, we wondered whether the E1's treatment ('loneliness increase') misled and confused its participants' information remembrance.

Finally, in the Treatment experiment (E4), the material-weight illusion associated with the '2020 loneliness percentage' parameter seems to have improved its overall efficiency, especially in terms of quickness. Besides, approximately 88% of its subjects remembered their previous answers. Therefore, in a nutshell, the main results were: (E2) Efficient but Unmemorable, (E3) Inefficient but Memorable, and (E4) Very Efficient and Very Memorable.

Table 1: Tabulation of the Primary Variables Results per Experiment.

Variables	**Digital (E2)**	**Control (E3)**	**Treatment (E4)**
Correct Assembling (%)	57.1	85.7	100
Response Accuracy (%)	92.857	80.952	83.333
Response Quickness (Seconds)	37.833	37.238	25.875
Efficiency (r = O/I)	2.454	2.173	3.220
Date Range (Days)	5,64	6,57	6,25
Memorability (%)	60	77.14	87.5
Experiment Duration (Minutes)	21.34	18.43	14.31

Despite the inconclusive strangeness' results, the design relevance in creating more engaging experiences with abstract data became evident throughout the current research. Moreover, according to the findings listed below, the area enables better ways of communicating data and may enhance emotional awareness regarding them.

Table 2: Tabulation of the Secondary Variables Results per Experiment.

Variables	Digital (E2)	Control (E3)	Treatment (E4)
Sample (Participants)	14	7	8
Gender (F% - M% - NB%)	64.28 - 28.57 - 7.15	42.85 - 57.15 - 0	50 - 50 - 0
Awareness (%)	71.43	28.57	62.5
Easiness (%)	35.72	25.72	45
Novelty (%)	57.14	100	100
Experience (%)	Insightful (85.70)	Surprising (100.00)	Insightful (62.50)
Aesthetics (%)	Graphics (85.70)	Gameplay (71.40)	Gameplay (75.00)

Discussion

By mitigating the former parameter's confusion, it is possible that the new weight treatment ('2020 loneliness percentage') positively impacted the E4 participants' general performance. It is necessary to acknowledge that the superior rates could be a matter of inferior date range between both questionnaires. Despite that, the present study still contributes to the design research area once it proves the influence of non-conforming physical weight on data physicalization, even though the results do not precise the scenarios where this influence is exclusively beneficial.

In this sense, the gameplay's narrative and open-ended questions likely affected the inconclusive Design Question results, as they captured most of every participant's attention. This inference by no means invalidates the decisions entangled in the design process. Especially because emerging studies in the field highlight the necessity of a more holistic and broad approach to physicalizations and visualizations due to its connection with human emotions. (Wang et al., 2019)

Besides, the statistics also led us to unexpected findings regarding gender and its connection to our Research Question. For example, the awareness results for the Digital study (E2) were the highest among all four experiments. Almost 72% of its participants attested posterior engagement with the loneliness topic in the week between both questionnaires. This constatation contradicted our expectations regarding embodiment and emotional connection to physical experiences.

After further investigating the possible causes of this observation, we cross checked the awareness values with the variable ‘gender’ and verified that almost 72% of the E2 participants were women or non-binary. In general, approximately 60% of women confirmed their engagement in conversations regarding loneliness posterior to their study participation, suggesting that females and non-binaries became more invested in the topic than males. Although acknowledging this finding is not surprising, we did not expect gender to play such a relevant role in the current research results.

Limitations

For several reasons (holidays, non-responses, pandemic, personal limitations), we could not ensure the same date range between questionnaires for every participant. Therefore, a mean was calculated for each experiment to minimize errors in the memorability results. Besides the narrow timeline and other constraints, the sample selection might have influenced the research findings. The lack of financial resources and the pandemic restrictions highly limited our access to volunteers. Hence, most participants were either design/architecture students or personal friends, family members, and acquaintances. Ultimately, this might mean they were more likely to be engaged in the studies' dynamics, for example.

Future Work

For future studies, associating the strangeness/surprise element to other aesthetic aspects, not as complex as conceptual expectancy, would surely lead to new curious findings. Or perhaps, systematically experimenting with size-weight illusions instead of material-weight could be an appealing approach. For the latter, however, we recommend simplifying the interactions by removing possible ‘distracting’ narratives, metaphors, or gameplays.

There are endless possibilities to investigate the impacts of strangeness on data efficiency and memorability. But, since the motivation to conduct the current research based on loneliness data was to raise meaningful debates and conversations, it is relevant to highlight the necessity of future initiatives on the topic as well. Mainly because the “practical potential of design to contribute to the profound cultural and ecological transitions [...]” (Escobar, 2018, p.X) is undeniable and urgent.

Conclusion

This paper suggests data physicalization may significantly leverage people's emotional engagement with abstract data. Despite the inconclusive results related to the material-weight illusion treatments and the surprise/strangeness feelings, several other design decisions – graphic elements, user experience, and storytelling – unquestionably impacted all experiments' efficiency and memorability results. Furthermore, according to the current research findings and theoretical background, engaging physicalizations and visualizations are likely to be appealing mediums for scientific knowledge disclosure and consciousness-raising initiatives.

References

Achotegui, J. (2019). Migrants Living in Very Hard Situations: Extreme Migratory Mourning (The Ulysses Syndrome). Psychoanalytic Dialogues, 29(3), 252–268. https://doi.org/10.1080/10481885.2019.1614826

Ajani, K., Lee, E., Xiong, C., Nussbaumer Knaflic, C., Kemper, W., & Franconeri, S. (2021). Declutter and Focus: Empirically Evaluating Design Guidelines for Effective Data Communication. IEEE Transactions on Visualization and Computer Graphics, 1.

https://doi.org/10.1109/tvcg.2021.3068337

Aragón, C., Jasim, M., & Mahyar, N. (2021). RisingEMOTIONS: Bridging Art and Technology to Visualize Public's Emotions about Climate Change. Creativity and Cognition. https://doi.org/10.1145/3450741.3465259

Baarck, J., Balahur-Dobrescu, A., Cassio, L.G., D`hombres, B., Pasztor, Z. and Tintori, G., Loneliness in the EU. Insights from surveys and online media data, EUR 30765 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-40246-6, doi:10.2760/28343, JRC125873.

Blair, E. (2015). A reflexive exploration of two qualitative data coding techniques. Journal of Methods and Measurement in the Social Sciences, 6(1), 14-29. https://doi.org/10.2458/v6i1.18772

Buckingham, G., Cant, J. S., & Goodale, M. A. (2009). Living in a material world: How visual cues to material properties affect the way that we lift objects and perceive their weight. Journal of Neurophysiology, 102(6), 3111–3118. https://doi.org/10.1152/jn.00515.2009

Camus, A. (2022). Myth Of Sisyphus: And Other Essays, The [E-book]. RANDOM HOU.

Chen, C., Härdle, W. K., & Unwin, A. (2007). Handbook of Data Visualization (Springer Handbooks of Computational Statistics) (2008th ed.). Springer.

Cross, N., Open University. Design Education Research Programme, & Open University. Design Education Research Programme. (1982). Designerly Ways of Knowing. Amsterdam University Press. 3(4), 221-227.

Dautrey, J., & Quinz, E. (2015). Strange Design: From Objects to Behaviours. It: Editions. France

Dewey J. (2005). Art as Experience. The Berkley Publishing Group. Penguin Books Ltd.

Dubberly, H. (2004) How do you design? A compendium of Models. Dubberly Design Office. San Francisco.

Dumičić, Z., Thoring, K., Klöckner, H. W., & Joost, G. (2022). Design elements in data physicalization: A systematic literature review. DRS Conference, Bilbao, Spain.

Escobar, A. (2018). Designs for the Pluriverse: Radical interdependence, autonomy, and the making of worlds. [Introduction]. In 1194500897 892578023. Durham: Duke University Press.

Findeli, A., & Russell, K. (2010) Design Research Network. Questions, Hypotheses & Conjectures. iUniverse., 286–303.

Frayling, C. (1993) Research in Art and Design. Royal College of Art, 1-5.

Friendly, M. (2006) A Brief History of Data Visualization. Handbook of Computational Statistics: Data Visualization, C. Chen, W. Härdle, A Unwin (Ed.), Heidelberg: Springer-Verlag, Ch. 1, pp. 1–34, 2007.

Garrett, J. (2010) The elements of user experience: user-centered design for the Web and beyond. Choice Reviews Online, 49(01), 49–0321. https://doi.org/10.5860/choice.49-0321

Griffin, J., & Mental Health Foundation (London, E. S. (2010). The Lonely Society? (ISBN

978–1-906162-49-8 ed.). Mental Health Foundation.

Howell, N., Chuang, J., de Kosnik, A., Niemeyer, G., & Ryokai, K. (2018). Emotional Biosensing. Proceedings of the ACM on Human-Computer Interaction, 2(CSCW), 1–25. https://doi.org/10.1145/3274338

Huron, S., Gourlet, P., Hinrichs, U., Hogan, T., & Jansen, Y. (2017). Let's Get Physical. Proceedings of the 2017 Conference on Designing Interactive Systems. https://doi.org/10.1145/3064663.3064798

Jansen, Y., Dragicevic, P., & Fekete, J. D. (2013). Evaluating the efficiency of physical visualizations. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/2470654.2481359

Jansen, Y., Dragicevic, P., Isenberg, P., Alexander, J., Karnik, A., Kildal, J., Subramanian, S., & Hornbæk, K. (2015). Opportunities and Challenges for Data Physicalization. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. https://doi.org/10.1145/2702123.2702180

Kaufman, G ., & Flanagan, M . (2015) . A psychologically "embedded" approach to designing games for prosocial causes . Cyberpsychology: Journal of Psychosocial Research on Cyberspace, 9(3), Article 5 . https://doi .org/10 .5817/CP2015-3-5

Kolb, A. Y., & Kolb, D. A. (2005). Learning Styles and Learning Spaces: Enhancing Experiential Learning in Higher Education. Academy of Management Learning & Education, 4(2), 193–212. http://www.jstor.org/stable/40214287

McCarthy, J., & Wright, P. (2004). Technology as Experience (The MIT Press). (MA).

Muratovski, G. (2016). Research for Designers: a Guide to Methods and Practice. Journal of Design, Business & Society, 2(2), 121–125. https://doi.org/10.1386/dbs.2.2.121_2

Offenhuber, D. (2020). What We Talk About When We Talk About Data Physicality. IEEE Computer Graphics and Applications, 40(6), 25–37. https://doi.org/10.1109/mcg.2020.3024146

Panksepp, J. (2004). Affective Neuroscience: The Foundations of Human and Animal Emotions (Series in Affective Science) (1st ed.). Oxford University Press.

Richardson, D. (2011). That Design is Not Art. Design Principles and Practices: An International Journal — Annual Review 5 (3): 517-526. doi:10.18848/1833-1874/CGP/v05i03/38058.

Saccone, E. J., Landry, O., & Chouinard, P. A. (2019). A meta-analysis of the size-weight and material-weight illusions. Psychonomic Bulletin & Review, 26(4), 1195–1212. https://doi.org/10.3758/s13423-019-01604-x

Sanders, L. (2008). ON MODELINGAn evolving map of design practice and design research. Interactions, 15(6), 13–17. https://doi.org/10.1145/1409040.1409043

Schön, D. (1987) Educating the Reflective Practitioner toward a New Design for Teaching and Learning in the Professions. Jossey-Bass.

Storr, W. (2020). The Science of Storytelling [E-book]. Macmillan Publishers.

Stusak, S., Schwarz, J., & Butz, A. (2015). Evaluating the Memorability of Physical

Visualizations. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. https://doi.org/10.1145/2702123.2702248

Stusak, S., Hobe, M., & Butz, A. (2016). If Your Mind Can Grasp It, Your Hands Will Help. Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction. https://doi.org/10.1145/2839462.2839476

Sosa, R., Gerrard, V., Esparza, A., Torres, R., & Napper, R. (2018). Data Objects: Design Principles For Data Physicalisation. Proceedings of the DESIGN 2018 15th International Design Conference. https://doi.org/10.21278/idc.2018.0125

Swan, T. (2018). The Anatomy of Loneliness: How to Find Your Way Back to Connection (New edition) [E-book]. Watkins Publishing.

Swaminathan, S., Shi, C., Jansen, Y., Dragicevic, P., Oehlberg, L. A., & Fekete, J. D. (2014). Supporting the design and fabrication of physical visualizations. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/2556288.2557310

Wang, Y., Segal, A., Klatzky, R., Keefe, D. F., Isenberg, P., Hurtienne, J., Hornecker, E., Dwyer, T., Barrass, S., & Rhyne, T. M. (2019). An Emotional Response to the Value of Visualization. IEEE Computer Graphics and Applications, 39(5), 8–17. https://doi.org/10.1109/mcg.2019.2923483

Zhao, J., & Moere, A. V. (2008). Embodiment in data sculpture: a model of the physical visualization of information. In Proceedings of the 3rd international conference on Digital Interactive Media in Entertainment and Arts (pp. 343-350).

Guedes Mesquita, Rebeca

Rebeca Guedes is a Brazilian designer passionate about critical thinking and innovation. She holds a Bachelor's degree in Industrial Design from the University of Brasília (2010), an undergraduate degree in Editorial Projects at UNA (2011), and a Master's degree in Integrated Design at Hochschule Anhalt (2022). With over 15 years of professional experience, she has explored with visual identity, branding, art direction, editorial design, social media, and UI/UX for banks, museums, publishing houses, advertising agencies, startups, and multinational enterprises. Currently, she is a UX Designer for SAP in Germany.

Thoring, Katja

Prof. Dr. Katja Thoring is Professor for Integrated Product Design at Technical University of Munich, Germany and Visiting Professor at Delft University of Technology, the Netherlands. She has a background in Industrial Design and researches on topics such as creative workspaces, technology-driven design innovation, design methodologies, and design education. Her main quest is to understand how the work environment can influence creativity and to turn these insights into tools and techniques for improving the innovation process.

The Artificial Lyricist: Prototyping an Interactive Opera for Humans and Machines

Mattias Rylander, Kristianstad University
Hedvig Jalhed, Mälardalen University
Kristoffer Åberg, Kristianstad University

Abstract

To probe into the artistic possibilities of Artificial Intelligence (AI) generating operatic elements, we have engaged in a practice-led inquiry as designers and artists. We took the process of prototyping a chamber opera with interactive features as our starting point, exploring how AI could work as a source of stimuli in opera productions, and how prototyping might add to the design and evaluation of AI integrated into an operatic context. Our core idea was to use AI to generate personalized lyrics in a dynamic opera libretto, based on input to the AI from individual visitors attending the operatic event. In response to visitors, the opera singer read and rendered the AI-generated text artistically in real-time and in a karaoke-like manner in accordance with the musical framework and the embodiment of the operatic character. Hence, the concept comprised both human-to-machine, machine-to-human, and human-to-human interaction. While some design elements stimulated the participating opera visitors, others stimulated the performing opera singer, supported by an informational framework composed verbally through a prototypical manuscript, audially through a prototypical accompaniment, and visually through a prototypical setting. The prototype was play-tested and evaluated in relation to our artistic intentions. The AI-based prototype added parameters to the artistic process such as sketching narrow AI for the operatic format and evaluating articulated qualities. Furthermore, we suggest that the conceptual artwork can be seen as an example of a contemporary turn in operatic evolution, with human performers forging not only bodily, but also intellectual relationships with machines.

Interaction Design, Chamber Opera, Artificial intelligence, Generative text, Prototyping

Opera brings together human capability and technological advancement – from musical instruments to theatrical machinery. Today, opera's relationship to digital innovations takes center stage. This paper reports on the prototype of an operatic concept informing a future elaborated opera, with real-time personalization of lyrics through Artificial Intelligence (AI) in live performances by human actors. The investigation was focused on the prototype's functionality and aesthetic compatibility, and the generative AI system's purposefulness and applicability in relation to primarily musical and interactive elements. Stemming from a practice-led methodology, we position the inquiry within the field of research in art and design, with the prototype supporting new knowledge for operatic practice and experience.

Focus and field

Setting up *The Oracle*, a prototypical opera with interactive features, our task has been to establish a framework for the generation of text, sound, and imagery – fitting together thematically and in an operatic manner with a synthesis of verbal, audial, and visual information.

Design concept

The design concept underpinning the prototype is the integration of AI as a generative text source for operatic libretti in visitor-interactive real-time performance – an artificial lyricist functioning as author and prompter for a karaoke-singing opera singer embodying a fictional character. We denote this artwork as an AI-based opera.

In early 2022, the idea of using generative AI as one among multiple authors of an opera led us to outlining this artistic concept. The concept was a collaboratively developed and the project was implemented through our own artistic practices, which besides musical composition and performance by David Hornwall included set design by Mattias Rylander, operatic performance by Hedvig Jalhed, and coding by Kristoffer Åberg. Joining forces not only as researchers, but also as artists, we concretized how AI could add to the composition by ways of generative text. Prophesying became the theme for the opera, with the Delphic oracle (Fontenrose, 1978) as a primary source of inspiration. From that, we created a concept for a one-on-one micro-opera of 3–4 minutes of action and music, centered around a soprano oracle who was not in contact with any divine forces, but with the digital realm that we turn to in the present day for prediction and advice. From questions posed by one opera visitor at a time, the oracle sang personalized answers.

Purpose

The overarching aim with the exploration was to test and evaluate libretto writing through generative AI as a supportive and innovative part of an operatic work. The study targeted the design elements in the conceptual art work and their qualities in an operatic context. The prototyping phase gave us an opportunity to evaluate the concept and beta-test the AI system in a live performance with participating visitors, before developing the artwork further.

The purpose of the project has been primarily artistic. We treat opera as a system for composed and aestheticized information, and our idea has been that AI can add specifically to dynamic lyrics. Opera, however, is not about efficient and clear communication, but rather about adding complexity and richness in order to challenge human cognition. The intention with the prototype has been to highlight problems and possibilities in the concept and inspire further elaboration and refinement.

Contextualization

In order to contextualize our inquiry, we frame our work through the notions of artistic prototyping, contemporary chamber opera, and machine intelligence.

Artistic prototyping

It has been argued that in the field of artistic research, artistic prototyping overlaps art and design (Arrigoni, 2016). A prototype can be persuasive, suggestive, or provoking, and it can stimulate action in order to facilitate artistic knowledge production. Key features of artistic prototypes have been identified as openness (to transformation) and fictionality (of speculative hypotheses), which support generativeness, participation, critique, and testing (Arrigoni, 2015). Prototyping can be used for evaluation and research, offering a context for artists in which to be creatively self-critical and promote constant reconsideration of ideas with a feedback effect on the emerging artwork (Popper, 1989). In order to be self-critical, the artistic intentions have to be articulated.

We subscribe to the view that an artwork should sustain engagement in line with Nguyen's idea of art as a game-like vehicle for a satisfying struggle to understand what is subtle and ambiguous (Nguyen, 2020b). This approach to artistic meaning derived from cognitive struggle is compatible with Boyd's evolutionary view of "art as a kind of cognitive *play*, the set of activities designed to engage human *attention* through their appeal to our preference for inferentially rich and therefore *patterned* information" (2009, p. 85, original emphasis). Boyd highlights that cognitive stimulation, social cohesion, individual status, and creative renewal are natural products of the evolutionary basis of art. Furthermore, a core feature of artistic experiences is how they produce enjoyable disagreement and discussion, based on the autonomy of aesthetic judgment (Nguyen, 2020a). With this theoretical framework, a professional artist produces aestheticized information patterns, considering the mechanisms of attention and taste. Artistically designed concepts and items provide cognitive challenges for the sake of increased cerebral activity that surpass the ordinary processing of the environment, causing rewarding stimulation both individually and collectively.

Contemporary chamber opera

Our general practice within contemporary chamber opera is based upon traditional operatic principles regarding characterization, autonomous vocalization, and live performance in resonant and wrought settings – but with an explorative and experimental approach to immersive and interactive features as well as contemporary and technology-laden sound and instrumentation. Our works are "ludo-immersive operas" (Jalhed, 2022), conceptualizing operatic experiences more as games or adventures through game design than spectacles for distanced audiences. We find opera an interesting field for practice-led research in that the systemism inherent in the relational aspects of operatic composition demands almost an engineering mindset. In artistic research, embodied human-machine relations in opera have been explored by, for instance, Ludvig Elblaus with Carl and Åsa Unander-Scharin (2016).

Machine intelligence

We adhere to Legg & Hutter's informal working definition of intelligence: "Intelligence measures an agent's ability to achieve goals in a wide range of environments" (Legg & Hutter, 2007, p. 12). We work at the level of intelligent agents or agentive systems of several agents possessing narrow AI (ANI), that is machine intelligence that may well have superhuman capability in a narrow domain, but lacks, for example, general or abstract problem-solving capabilities in a wide range of environments, on par with human-level intelligence (Noessel, 2017; Russell & Norvig, 2022).

Related work

Other experimental operas have involved AI in different ways during recent years. For instance, in *Chasing Waterfalls* (Lee et al., 2022), lyrics and vocals are generated through AI, and in *La Fabrique des Monstres* (Ghisi et al., 2018), AI imitates the sonic idiom of classical opera. Related concepts are also the system *LyricJam*, generating lyric lines for instrumental music (*Researchers Develop Real-Time Lyric Generation Technology to Inspire Song Writing*, 2021), and the tool *Deep-speare*, intended for automatic poetry composition that advances aesthetic form such as rhyme and meter, but with found shortcomings in readability and emotional expression (Lau et al., 2018).

Research question and delimitations

Based on our view of art described in the contextualization, desired qualities in the artwork were obscurity, novelty, attractivity, and controversy. We also sought to articulate qualities concerning the agentive system. Our research question concerned the effect of AI on the design work, and the value of AI in an operatic context with both creative (open-ended and expanding) and critical (closed-ended and restraining) potential: What does an AI-based prototype add to the operatic process and artwork?

We limited our inquiry to the above issues, and although the concept touches upon a number of other topics, we have not included any remarks about, for instance, immersive factors, game mechanics, and musical composition.

Methods

We have used a practice-led approach to develop, design, and evaluate the different elements and features within the artwork.

Practice-led approach

A practice-led approach allows researchers in art and design to advance knowledge within practice and leads to new understanding about practice (Candy & Edmonds, 2018). We used this kind of research iteratively in a developmental exploration.

Artistic development method

The Oracle was developed through a parallel creation of manuscript, accompaniment, and setting, with mutual adjustments. As in all opera, accommodation of human performance and perception was key. By drafting and revising possible system relations, text patterns with grammar and content matrices, sheet music, costume variants, and surrounding projections, as well as rehearsing, the prototype was developed with overlapping steps.

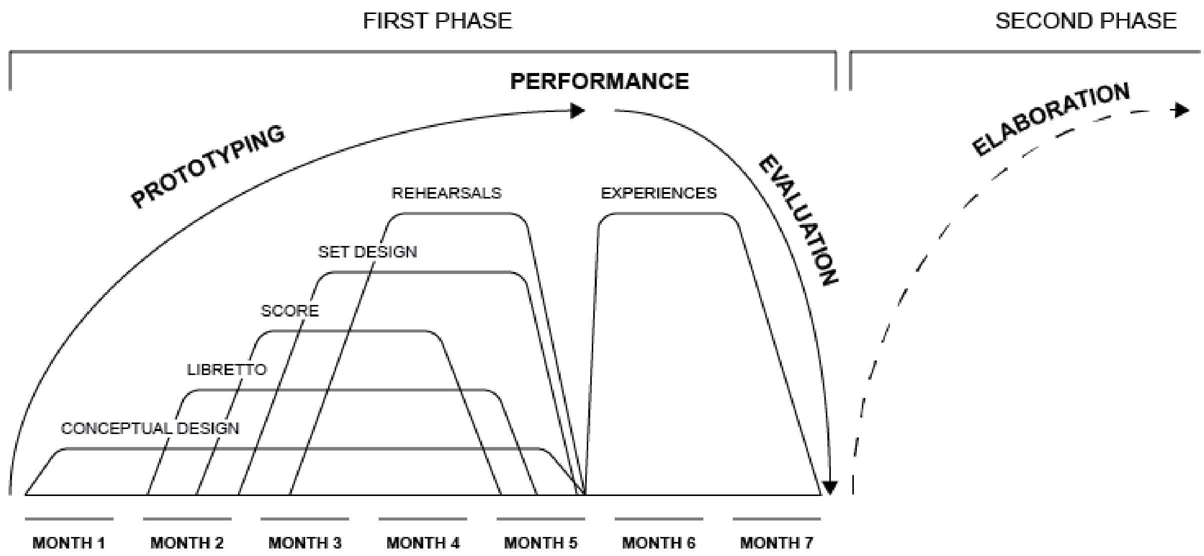


Figure 1: Iteration arc with overlapping elements in the prototyping phase.

Conceptual design method

The concept was developed from the basic idea of integrating AI into opera in order to combine human performance with contemporary machinery. After setting up the work roles, the design of the agentive system and the compositional elements emerged dialectically.

Interaction design of narrow AI entails sketching and prototyping an agentive system of one or more intelligent agents, each interacting with other machines or human agents by perceiving its own environment, and acting upon that environment, with the agent's behavior described by an agent function mapping percepts to actions. Interaction programming in this case concerned the implementation of these intelligent agents consisting of an architecture (computing devices with physical sensors and actuators) and an agent program that implements the agent function (Noessel, 2017; Russell & Norvig, 2022).

Traditional sketching with pen on paper explored issues related to the operatic experience, from system design with relations and interactions among agents, to user interfaces for visitor input and generative libretto output, and to algorithm and database designs for the Natural Language Processing (NLP) of input into output. Embodied sketching (Márquez Segura et al., 2016) was undertaken to bodystorm ideas and increase sensitization for design of physical and spatial human–AI interactions in the prototype's environment. Sketching in the medium of code (Löwgren, 2016) was necessary for the high-fidelity design and evaluation of the agent functions and their underlying algorithms. The agent functions were sketched in the Python programming language in Google Colaboratory, which is a computational notebook environment combining executable programming code with the possibility of text documentation (Google Research, n.d.).

Code sketches were further developed into prototypes in Google Colaboratory and tested in a series of rehearsals to improve software quality, and then migrated to a prototype web application encompassing the system of machine agents in the form of their related agent programs, whereupon the web app was further developed and tested. The web application was implemented in Python using the Flask micro web framework and SQLAlchemy database toolkit; OpenAI's GPT-3 application programming interface was used for natural language processing of text input into generative text output; and HTML, CSS, and the jQuery JavaScript library were used for text presentation. It was deployed on a cloud platform for access via any web browser client running on a PC, tablet, or smartphone.

Design evaluation method

We sought to articulate qualities for the evaluation of the prototype. While our general artistic intentions concerned the prototype's ability to generate obscurity, novelty, attractivity, and controversy, additional desired qualities associated with the AI-based concept emerged as oddity (peculiar and incoherent content) and stability (reliable and predictable performance), and beyond human capabilities. The agents' abilities to process and convey information within the system were also subject to evaluation.

After the event, the prototype was evaluated by us artist–researchers as artistic users, using an evaluation matrix to address qualities with the following score set:

0 = No reported or documented occurrence
1 = Single reported or documented occurrence
2 = Multiple reported or documented occurrences
3 = Consistently reported or documented occurrences

Rather than the positive features of the prototype, we have chosen to evaluate the shortcomings. In this way, it was possible to measure both weak links and the compositional effect.

Documentation of artistic performance

The play-testing event took place at PlayLab, Skövde, and was limited to a continuous performance time of about one hour, and the artistic performance was documented through audio/video recordings.

Visitor experiences

A visitor survey aimed to capture individual experiences and impressions anonymously from the play-testing event. The scope of the evaluation matrix and the survey design overlapped in some parts. The survey contained ten questions about interaction and immersion:

1. Have you been to immersive/interactive opera or similar things earlier?
2. How much experience of opera in general do you have from earlier?
3. Did you ask the oracle a question?
4. If you asked a question of the oracle, what question did you ask?
5. If you asked a question, what did you comprehend from the text that was sung in response?
6. To what extent did you think that your question was answered?

7. How well were your expectations met?
8. Did it feel like time went faster than usual?
9. Did you feel like you were in a different place from usual?
10. Is there anything more that you want to tell?

Results

The results of the prototyping phase emerge as sketches of the agentive system and user experiences. The prototypical system was based on four interacting agents, and the prototype constitutes a working model for future elaboration.

Figure 2: System overview with the interacting agents.

The Oracle was developed for a public venue with a visually closed-off but audially permeable cylindrical 360° cave, with its inside covered by a projection of AI-generated images and video. The music was composed for soprano and electronics and the multisensory experience was supposed to create an impulse to action (c.f. Boden, 2004). The piece was in stasis as long as a visitor didn't interact as a player, and the choice to participate by playing – that is, to make an effort to overcome unnecessary obstacles (Suits, 2014) – implied an opportunity to experience something different from what a passive observer would.

The prophecies had to be aestheticized and presented in a way that matched the music and the singer, with vowels applied in relation to tone frequency and voice type, as well as allowing for breathing needs, line length, and syllable count. Unconventional and surprising combinations of words and nonsensical syntax sometimes occurred. The singer was visually isolated, and only one player at a time was allowed to enter the cave after having submitted a question at an altar. Other visitors could still hear both music and lyrics, but were cut off from a view of the oracle and the visual design within the cave. The secretive design made it possible to evaluate several separate consultations with the oracle.

Figure 3. Photos from the playtesting event. Visitor at the altar before stepping into the cave, the oracle in the cave from outside, and the opera singer's view inside the cave with a seat for the incoming visitor and a display for the AI-generated lyrics.

Agentive system

The prototype agentive system was composed of the human agents consultant (visitor), priest (programmer) and oracle (singer), and the machine agent deity (AI software program). The machine part of the system was accessible to the human agents priest and oracle via a web browser client. The deity together with the altar, librettist, and teleprompter, were all simple reflex agents, i.e. they selected their actions on the basis of current input (Russell and Norvig 2022), in a stimulus-response manner. The agents of the system and their interactions is outlined in order of appearance in the performance:

Consultant (human): The visitor as consultant approached the altar for a consultation with the oracle.

Priest (human): The priest asked the consultant to tell him their name and ask their question.

Altar (machine): The priest entered the consultant's name and question into the altar's user interface.

Deity (machine): The deity took the consultant's name and question from the altar as input to its own agent program, as follows.

Preprocessing

The narrow AI used for generating text, OpenAI's GPT-3, took as input a text prompt consisting of instructions and potentially some context and examples (OpenAI, n.d.-b). In the deity's preprocessing algorithm, this prompt was constructed out of an example text with a certain line and syllable format, an instruction to write the arioso part of the libretto over six lines (each line of a certain syllable count), and specific instructions for generating the content of each of the six lines.

In research on Greek mythology and religion, the responses of the Delphic Oracle of ancient Greece have been classified according to different modes of expression (Fontenrose, 1978). The present-day machine deity randomly selected one of these modes as one basis for generating its response, with associated rules and further selectors for generating the content of each line making up the expected response from the oracle. Thus, the question "What brings the oracle joy?", coupled with the mode of expression "an ambiguous prohibition", might generate the following instruction as part of the prompt for GPT-3:

Write one arioso for a libretto of exactly six lines annotated in this style.
The first line must be 9 syllables long and start with the word ">Don't" followed by an ambiguous prohibition, as a response to the question "What brings the oracle joy?"
The second line must be 9 syllables long and start with the word ">Don't" followed by an ambiguous prohibition, as a response to the question "What brings the oracle joy?"
The third line must be 7 syllables long and start with the word ">" followed by a response to the question "What brings the oracle joy?"
The fourth line must be 7 syllables long and start with the word ">You must" followed by an ambiguous prohibition, as a response to the question "What brings the oracle joy?"
The fifth line must be 7 syllables long and start with the word ">You must" followed by an ambiguous prohibition, as a response to the question "What brings the oracle joy?"
The sixth line must be 4 syllables long and start with the word ">" followed by a short response to the question "What brings the oracle joy?"

Text generation

The full prompt was sent via the application programming interface of OpenAI's GPT-3 Davinci-002 model for understanding and generating natural language, set to a high degree of diversity in the text completions returned as output. Davinci was selected due to its capabilities in understanding the intent of text and following instructions (OpenAI, n.d.-a).

Postprocessing

The generative text completion returned by GPT-3 was checked and processed by a further algorithm, sorting the generated lines according to initial words, duplicating or generating further lines if one or more of the six lines were missing in the completion, and adjusting line length according to word, and hence rough syllable count by multiplying or slicing lines if either too short or too long, respectively. All these algorithmic operations were undertaken in order to keep the response more in line with the creative direction for the arioso format as embodied in the instruction, and hence more suitable for the oracle to perform. As an example, the above question might result in the following response, also comprising the arioso of the libretto:

Don't try to understand
Don't try to think
Just do what brings you
You must not question
You must not doubt
It is what it

The deity's output comprising mode and response was saved together with the consultant's first name and question in a database. The remaining agents were:

Librettist (machine): The librettist took as input the response part of the deity's output, recombining the response in the form of an arioso into the stretta part of the libretto, and fitting the arioso and stretta in between the recitativo and affirmatio parts, and into the full libretto.

Teleprompter (machine): The teleprompter took the mode and libretto as input, and output them via its screen in the cave.

Oracle (human): The oracle read the mode and rendered the libretto presented by the teleprompter.

User experiences

The play-testing event took place in November 2022, with the opportunity to facilitate user experiences of the design components put together as a tentative whole. The prototype was performed live 17 times with different visitors, appearing as consultants who provided the AI system with questions for the oracle. The anonymous survey was answered by nine visitors. All questions and responses were recorded from and saved in the project database.

Human-to-machine interaction

The consultants posed their questions orally to the priest, who submitted them textually. Despite reports of insufficient introductions for the guests, no visitor failed to provide applicable information for the AI agent with the aid from the programmer.

Machine-to-human interaction

Technically, the system proved to be reliable and generated new and personalized content for all consultants. All responses from the AI could be used as a basis for an answer, although some lacked either metrical compatibility or coherent meaning. However, this could be used as a poetical expression for the fictive oracle's own confusion.

When the AI agent failed to provide the singer with sufficient text, the performer chose to edit the lyrics ad hoc. This emergent tactic came with an improvisatory approach. In traditional repertory opera, singers sometimes improvise exclusively musically in melodic embellishments, but not textually. In the contemporary practice of opera improvisation, lyrics, music, and action can be improvised altogether and "the audience is often invited to give suggestions for the starting points of the performance" (Wilén, 2017, p. 22). With the AI agent as author and prompter, however, the direct input source differed from opera improvisation. Moreover, the opera singer was provided with a, more or less, complete text, with the potential to adjust details, instead of inspirational key words as in opera improvisation.

Human-to-human interaction

The opera singer received information from the AI through the teleprompter but there was no feedback from the singer to the AI agent. The singer interacted with the visitors as they took part in the prophecies face to face, acting as oracle and consultants respectively. This included eye contact and gestures. No visitor interacted audially with the singer.

The comments from the survey display how different visitors paid attention to various things: the interaction with the singer (Respondent 2), the uncertainty of how to interact due to the lack of explicit instructions (Respondent 7), the wish for preparatory and parallel activities (Respondent 8), and the ambient mood (Respondent 9), for example.

Six respondents reported having asked the oracle a question, and the average rating of how well they thought their questions were answered by the oracle was 3,33 on a scale from 1 (poor) to 5 (good). None of these rated their answer as 1, so some purposefulness could be derived from the lyrics in all cases.

Evaluation scores

The scores in the evaluation matrix show that the critical links within the information system were the program and the singer. A deficit came forth in the occasional mismatch between the AI agent's metrical and grammatical ability and the opera singer's capacity to live-edit scarce or confounding information sufficiently.

The artistic quality of obscurity can encompass instructions for participation if the interaction is regarded as an integrated part of the collective performance. And if novelty is found in the obscurity of instructions, it adds challenge. The question then becomes whether the challenge was measured and communicated.

SCORE	0 = No reported or documented occurrence	1 = Single reported or documented occurrence	2 = Multiple reported or documented occurrence	3 = Consistently reported or documented occurrence
The visitor failed to provide the programmer with applicable information (first agent)	X			
The programmer failed to provide the program with applicable information (second agent)	X			
The program failed to provide the singer with applicable information (third agent)			X	
The singer failed to provide the visitor with applicable information (fourth agent)			X	
The artwork failed to make the visitors wonder about how to interpret it (obscurity)	X			
The artwork failed to make the visitors wonder about how to interact with it (novelty)	X			
The artwork failed to steer the visitors' attention (attractivity)	X			
The artwork failed to spark strong opinions (controversy)		X		
The artificial lyricist failed to produce peculiar or incoherent content (oddity)		X		
The artificial lyricist failed to perform in a reliable or predictable way (stability)			X	

Table 1: Evaluation matrix with scores for the prototype.

Discussion

The empirical research conducted in relation to the prototype has enabled the creation of both theoretical and practical knowledge in the field of art and design, for example conceptual and experiential discoveries such as the difference between agents and the changed artistic workflow. Below, we discuss issues of narrow AI and operatic evolution in relation to the research question.

Narrow AI

Integrating AI into opera adds to the artistic process in terms of sketching and design elements, with the results from this study applicable beyond the generation of operatic elements to AI prototyping practices in general. Sketching and prototyping intelligent agents actually using narrow AI technology such as GPT-3 becomes both necessary and useful for understanding the capabilities of the technology, as its possibilities and limitations are inherent and present, in contrast to low-fidelity "Wizard of Oz" experiments where humans assume the role of simulating intelligent computers (c.f. Cross, 2001). There thus needs to be a closer correspondence in higher fidelity between (computational) sketch, prototype, and artwork; the technology has to work to some extent, and not just pretend to work, in order to inform design. Lower fidelity techniques will still have their place in the early phases, but the support of accessible AI tools and technologies may be necessary quite soon thereafter in the design process.

As noted by Schön (1992), designing can be seen metaphorically as a reflective conversation with the design materials of a situation. Prompting GPT-3, having it respond, reflecting on the responses, and having the responses iteratively inform the prototype design of the deity, is a conversation on one level where the design material of narrow AI is actually conversational on another level. One reflection prompted back by this conversation is: Who, or what, is the artificial lyricist? Static parts of the libretto emerged in conventional manner, with the composer's creative direction manifested in the prototypical manuscript of a libretto example with themes, lines, and syllables. It was further elaborated by the singer as a set of rules and yet further extrapolated by the programmer into program code, leveraging the possibilities of the digital and AI technologies. Dynamic parts were further shaped in iterative code executions and rehearsals, and ultimately through the unpredictable approaches of the visitors and their consultations, processed by the deity, whose generated responses were either sung or substituted by the singer's improvisations. The lyricist could thus be viewed as the entire system of human and machine agents, the form and content of the libretto stemming from conversational interactions throughout the prototype process up to and into the performance.

Operatic evolution

Our contribution to the integration of AI into operatic art follows a contemporary line of artistic exploration and research producing new knowledge about operatic practice. AI-generated text offers a third way in addition to memorized and improvised text in opera. As stated in the beginning of the paper, opera has always evolved through new combinations of human performance and technological innovation. So, if it is a general feature of opera to display unaided human abilities to be seen, heard, and understood in machine-based surroundings, what can be derived from AI? Just as instrumentalists have tended to anthropomorphize their instruments (Cypess & Kemper, 2018) or even believed that they have incorporated their instrument as part of themselves (Nijs, 2018), the tendency to imagine AI as human-like entities flourishes (Salles et al., 2020). But while we have material relationships with musical instruments, our relations with non-embodied AI agents are intellectual and stimulated by what they generate, not what they are. In our prototype, the AI agent contributed with content that could be interpreted as poetical and mystical. From this we suggest that AI offers a way to turn operatic evolution toward artistic productions that involve intellectual and not only material stimulation from machines.

When engaging in discussions about art, people usually try to figure out the artist's intentions and incentives, which implies curiosity about human agency. But the anthropomorphic agency we like to think that AI agents have is an animistic illusion (c.f. Gopnik, 2022) – an illusion actualized already by Turing's imitation game (1950). The question is how well we can disguise AI by artistic means in order to sustain the illusion of agency in relation to the receiver of textual content. The aesthetic effect would not be the same if the visitor simply read the libretto – or the code.

Conclusions and future research

The results demonstrate the need for further research into sketching and prototyping narrow AI, moving from simple reflex agents to more complex agents that achieve goals or learn over time (Russell & Norvig, 2022). Such research may follow different but compatible tracks, starting from the notion illustrated by the present project with human agents extended by AI (Hernández-Orallo & Vold, 2019), by building on Schön's view of sketching as conversations with design materials like interaction (Hornbaek & Oulasvirta, 2017) and intelligence (Holmquist, 2017), not least machine learning (e.g. fine-tuning an oracular language model) for NLP (Yang et al., 2019). As demonstrated by the artificial lyricist system, one could explore "networked computational things not only as designed artifacts or technological enablers but also in terms of agents in a design space where they actually participate" (Giaccardi & Redström, 2020, p. 35). From agents as participatory designers, and, in supporting performers not only through generative text but image and music too, perhaps then also to agents as participating game characters, learning over time.

By evaluating the prototype as an agentive information system and aesthetically balanced artwork, we conclude that relevant properties were put to the test. The matrix could work as a model for evaluation, but the result could be better validated with a survey design directly connected to the matrix and more quantitative stats. This kind of AI-based opera expands the toolbox of opera artists as it adds thematic content in a stylistic way and enables dynamic and personalized lyrics. This unburdens the singer from both memorization and improvisation of text but demands split attention and live-editing skills. At the same time, the concept requires the visitor to feed the system in order to get something back, hence depending on input.

AI can be used instrumentally in opera but requires human processing in order to be artistically interesting. The dualistic division of labor between authoring device producing thought and mediating singer producing sound can, in the optimal case, enhance the artistic experience as a whole. However, with the technical limitations at hand, it may also impact on the singer's attention as she takes on the task of proof-reader and editor in action. Future research could therefore also include comparative studies on the creative range and critical limitations in AI-based opera versus human opera improvisation when it comes to qualities such as oddity and stability.

Acknowledgments

We would like to thank our colleagues and collaborators for their contributions to *The Oracle*. We are also most grateful for all feedback from the participating visitors in the play-testing event.

References

Arrigoni, G. (2015). Understanding Artistic Prototypes Between Activism and Research. Computation Communication Aesthetics and X, Glasgow, Scotland.

Arrigoni, G. (2016). Epistemologies of prototyping: Knowing in artistic research. Digital Creativity, 27(2), 99–112.

Boden, M. A. (2004). The Creative Mind: Myths and Mechanisms (Second Edition). Routledge.

Boyd, B. (2009). On the Origin of Stories: Evolution, Cognition, and Fiction. Harvard University Press.

Candy, L., & Edmonds, E. (2018). Practice-Based Research in the Creative Arts: Foundations and Futures from the Front Line. Leonardo, 51(1), 63–69.

Cross, N. (2001). Can a Machine Design? Design Issues, 17(4), 44–50. https://doi.org/10.1162/07479360152681083

Cypess, R., & Kemper, S. (2018). The Anthropomorphic Analogy: Humanising musical machines in the early modern and contemporary eras. Organised Sound, 23(2), 167–180.

Elblaus, L., Unander-Scharin, C., & Unander-Scharin, Å. (2016). Workshop: Which scenic subjects may emerge when interacting with machines through vocal and bodily virtuosity? Carpa4: The Non-Human and the Inhuman in Performing Arts – Bodies, Organisms and Objects in Conflict. Carpa, Helsinki.

Fontenrose, J. E. (1978). The Delphic Oracle: Its Responses and Operations with a Catalogue of Responses. University of California Press.

Ghisi, D., Peyret, J.-F., & Meier, R. (2018). La Fabrique des Monstres.

Giaccardi, E., & Redström, J. (2020). Technology and More-Than-Human Design. Design Issues, 36(4), 33–44. https://doi.org/10.1162/desi_a_00612

Google Research. (n.d.). Colaboratory. Google Colab. Retrieved January 6, 2023, from https://research.google.com/colaboratory/faq.html

Gopnik, A. (2022, July 15). What AI Still Doesn't Know How to Do; Artificial intelligence programs that learn to write and speak can sound almost human—But they can't think creatively like a small child can. Wall Street Journal.

Hernández-Orallo, J., & Vold, K. (2019). AI Extenders: The Ethical and Societal Implications of Humans Cognitively Extended by AI. Proceedings of the 2019 AAAI/ACM Conference on AI, Ethics, and Society, 507–513. https://doi.org/10.1145/3306618.3314238

Holmquist, L. E. (2017). Intelligence on tap: Artificial intelligence as a new design material. Interactions, 24(4), 28–33. https://doi.org/10.1145/3085571

Hornbaek, K., & Oulasvirta, A. (2017). What Is Interaction? 5040–5052.

Jalhed, H. (2022). An Operatic Game-Changer: The Opera Maker as Game Designer and the Potentials of Ludo-Immersive Opera. University of Gothenburg.

Lau, J. H., Cohn, T., Baldwin, T., Brooke, J., & Hammond, A. (2018). Deep-speare: A joint neural model of poetic language, meter and rhyme. Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics (ACL 2018).

Lee, A., Neudecker, C., Beyer, S. S., Eule, J. C., & kling klang klong. (2022). Chasing Waterfalls.

Legg, S., & Hutter, M. (2007). Universal Intelligence: A Definition of Machine Intelligence. https://doi.org/10.48550/ARXIV.0712.3329

Löwgren, J. (2016). On the significance of making in interaction design research. Interactions, 23(3), 26–33. https://doi.org/10.1145/2904376

Márquez Segura, E., Turmo Vidal, L., Rostami, A., & Waern, A. (2016). Embodied Sketching. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, 6014–6027. https://doi.org/10.1145/2858036.2858486

Nguyen, C. T. (2020a). Autonomy and Aesthetic Engagement. Mind, 129, 1127–1156.

Nguyen, C. T. (2020b, August 17). Art Is a Game. Forum for Philosophy. https://blogs.lse.ac.uk/theforum/art-is-a-game/

Nijs, L. (2018). The Merging of Musician and Musical Instrument: Incorporation, Presence, and Levels of Embodiment. In M. Lesaffre, P.-J. Maes, & M. Leman (Eds.), The Routledge Companion to Embodied Music Interaction (pp. 167–180). Cambridge University Press.

Noessel, C. (2017). Designing Agentive Technology: AI That Works for People. Rosenfeld Media LLC.

OpenAI. (n.d.-a). Models. Models. Retrieved January 6, 2023, from https://beta.openai.com/docs/models

OpenAI. (n.d.-b). Quickstart. Quickstart Tutorial. Retrieved January 6, 2023, from https://beta.openai.com/docs/quickstart

Popper, K. (1989). Creative Self-Criticism in Science and in Art. Diogenes, 37(145), 36–45.

Researchers develop real-time lyric generation technology to inspire song writing. (August 10, 2021). https://uwaterloo.ca/news/media/researchers-develop-real-time-lyric-generation-technology

Russell, S. J., & Norvig, P. (2022). Artificial Intelligence: A Modern Approach, 4th Global ed. (Fourth edition, global edition). Pearson.

Salles, A., Evers, K., & Farisco, M. (2020). Anthropomorphism in AI. AJOB Neuroscience, 11(2), 88–95.

Schön, D. A. (1992). Designing as reflective conversation with the materials of a design situation. Knowledge-Based Systems, 5(1), 3–14. https://doi.org/10.1016/0950-7051(92)90020-G

Suits, B. (2014). The Grasshopper: Games, Life, and Utopia (Third Edition). Broadview Press.

Turing, A. M. (1950). Computing Machinery and Intelligence. Mind, 59(236), 433–460.

Wilén, S. (2017). Singing in Action: An inquiry into the creative working processes and practices of classical and contemporary vocal improvisation. Lund University.

Yang, Q., Cranshaw, J., Amershi, S., Iqbal, S. T., & Teevan, J. (2019). Sketching NLP: A Case Study of Exploring the Right Things To Design with Language Intelligence. Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, 1–12. https://doi.org/10.1145/3290605.3300415

Mattias Rylander

Mattias Rylander is senior lecturer in Informatics and Graphic Design at Kristianstad University. He holds a Master's degree in Fine Arts. He is a visual artist, graphic designer, and set designer, and his work includes video art, illustrations, literary productions, and scenographic interiors. During the last decade, he has created set designs for a number of experimental chamber opera productions, both on conventional stages, in black boxes, and in urban exploring venues and found spaces.

Hedvig Jalhed

Hedvig Jalhed is senior lecturer in Chamber Music and Chamber Opera at Mälardalen University and interim director for Inter Arts Center, the center for cross-disciplinary research and practice within the Faculty of Fine and Performing Arts at Lund University. She is a professionally trained opera singer with a Master's degree in Musical Performance and Doctorate degree in Performance in Theatre and Music Drama. Her artistic research concerns the development of operatic practice in contemporary and conceptual works with a special focus on operatic game-design and issues regarding immersion and interaction. Besides her academic career, she has founded the independent chamber opera company Operation Opera and is appointed artistic director for Halland Opera & Vocal Festival on behalf of Region Halland.

Kristoffer Åberg

Kristoffer Åberg is lecturer in Digital Design at Kristianstad University. He has a Master's degree in Computer Science specializing in Human-Computer Interaction. With a long career as interaction designer previously in the telecoms industry he now shares his time between his advanced design consultancy, lifestyle businesses, and academic research and teaching, all centered in computational interaction design with and of emergent and speculative AI technologies.

Graft-games: Experiential prototyping for the exploration of crossovers between craft and gaming

Gemma Potter, Manchester Metropolitan University, Manchester, UK.

Abstract

This paper presents an experimental prototyping approach, termed 'grafting', for investigating theoretical crossovers between craft practice and the play of video games. It presents a case study of prototype 'graft-game' *Hazuki Knit,* developed as a probe for exploring an emerging theoretical field of study that acknowledges embodied skill within the play of videogames aligning it with craft labour. In particular, it proposes a method of prototyping in which an existing game is directly grafted onto a craft activity in order to enable the direct observation of its impacts upon embodied and inarticulable actions of participants during grafted gameplay at a series of themed public events. Through discussion, it presents grafting as a method for interrogating the potentialities brought about through joining these two related yet distinct activities. Utilising key findings from a case study of prototype 'graft-game' *Hazuki Knit* conducted by the author between May 2018 and June 2019 this paper reveals that directly joining craft with a digital game can lead to high-risk gameplay that can negatively impact the quality of the craft output.

Craft; Gaming; Graft-game; Crossovers; Prototyping

There is much existing research that investigates the collaborative nature of craft (Felcey et al., 2017; Adamson, 2007), its ability to connect people (Gauntlett, 2018) and transcend traditional boundaries, especially in relation to digital technologies (Rosner, 2010; Golsteijn et al., 2014). In recent years there has been a growth in theoretical research within games studies that acknowledges the skilled aspects of videogame play from authors such as such as Brock & Johnson (2021), Brock & Fraser (2018), Nørgård (2012) and Reeves et al (2009). There is, however, little empirical research that directly explores links between craft and gaming, especially from the perspective of creative practice. Alongside this, an increase in accessibility to digital fabrication and physical computing in recent years has created "opportunities to merge crafting activity with electronic games" (Sullivan and Smtih, 2017: 38) leading to exploration of alternative games and custom controllers. In their 2017 paper *Designing Craft* Games, Sullivan and Smith presented reflections on three 'Craft games' that use craft as either a method of creating input devices or components for games (digital or non-digital), or craft as a physical output for a game. None of these examples, however, interrogate the impact that merging these two activities has upon the craft or gaming aspects. This paper presents a case study from the completed doctoral research of the author to discuss an experimental prototyping approach in which craft and gaming are explored in direct relation to one another, through a process referred to as 'grafting'. This approach did not seek to join craft with gaming to merely create a new input or output for a game. Instead, 'grafting' aimed to bring craft and gaming together as an active method of enquiry for exploring the potential impacts of combining these two forms of activity. The term 'grafting' is borrowed from horticulture where it is used to describe "joining parts of two or more plants so that they appear to grow as a single plant" (Bilderback et al., 2014: online). In using grafting as both a metaphor for the approach and a description of the method employed in connecting a game and a craft activity through a direct and physical join, this study aimed to explore and capture the potential impacts that arise through grafted gameplay.

Thematic Crossovers

Within horticulture, grafting is commonly carried out with trees and shrubs and, although the parts "do not have to be from the same species" (Iannotti, 2020: online), they do need to be compatible. The characteristics of each part are thus carefully considered before grafting. This research took a similar approach by considering the commonalities between craft and gaming practices through the identification of theoretical crossovers. An analysis of key craft and gaming literature established three key areas of crossover which are considered fundamental to both.

1) Habitual practice

Learning through habitual practice has been attributed to the acquisition of craft-based skill (Sennett, 2008; Risatti, 2013). As stated by Sennett "skill is a trained practice" (Sennett, 2008:37) and in "learning a skill, we develop a complicated repertoire" (Sennett, 2008:50) of routinized procedures, embedding them through "the conversion of information and practices into tacit knowledge" (Sennett, 2008:50). Habitual practice refers to the process of embedding knowledge over time through the repetition of actions. To gain and develop skill, to embed it into our knowledge system, we must be in action, as "going over an action again and again […] enables self-criticism" (Sennett, 2008:37-38) on which skill development depends. "As a person develops a skill, the contents of what he or she repeats change"(Sennett, 2008:38). This way an "open relation between problem solving and problem finding"(Sennett, 2008:38) occurs through which a rhythm of solving and opening repeats over and over in a progressive manner. This is key to the acquisition of skill over time.

The playing of video games requires a similar acquisition of skill with players displaying "remarkable dexterity developed through many hours"(Reeves et al., 2009:205) of gameplay through which they develop a deep understanding of their 'material': the game. Through adopting Sennett's analysis of craft and applying it to gaming labour, Brock and Fraser present an account of gameplay that "recognises that players have to establish technical skill to negotiate the increasingly demanding, complex puzzles that contemporary computer games offer"(2018:1221). Through their analysis of *Dota 2*, the authors discuss how players acquire "sense data about the game through a series of tutorials"(Brock and Fraser, 2018:1224) in which the player learns and practices the "basic mechanics of right-clicking, scrolling, and re-centering"(Brock and Fraser, 2018:1224) to progress their skills. Through practice "*Dota 2* players constantly adapt their grip to establish control over the game"(Brock and Fraser, 2018:1224). The repetitive actions of pressing buttons in the problem-solving environment of a videogame thus align with habitual practice in the context of craft expertise.

2) The desire to do well

Sennett states that “[c]raftsmanship names an enduring, basic human impulse, the desire to do a job well for its own sake” (2008:9). It is this impulse that highlights the craftsman’s “aspiration for quality” and “evidence of truly rewarding work” (Brock & Fraser, 2018:1219) and it is Sennett’s analysis of craft labour that Brock and Fraser (2018) apply to, and align with, the act of gaming. According to Jesse Schell “doing something ‘for its own sake’ […] is an important characteristic of play. If we don’t like to do it, it probably isn’t play” (2020:39). To this end, craft and gaming could be classified as intrinsically motivated activities, without external reward.

According to Juul, a game is:

> A rule-based system with a variable and quantifiable outcome, (…) the player exerts effort in order to influence the outcome, the player feels emotionally attached to the outcome, and the consequences of the activity are negotiable. (Juul, 2011:36)

Variable outcomes, be they scores or items created, are what make a game desirable to play (Juul, 2011) and in this sense, match the goal of craft to produce an object or artefact. According to Sennett, it is the “aspiration for quality” that drives a craftsman “to improve, rather than get by” (2008:24). The outcomes of a video game tend to remain virtual, but both outputs, whether physical or virtual, hold value to the player and the craftsperson alike. Both act as evidence of actions and both player and maker exert effort in the production or achievement of their outcome. In doing so, the player and the maker develop a desire to improve these outcomes through practice.

3) Minimising risk

It is the craftsman’s “desire to do a job well for its own sake” (Sennett, 2008:9) that highlights the craftsman’s “aspiration for quality” (Brock & Fraser, 2018:1219). According to Pye, in craft “the quality of the result is not pre-determined, but depends on the judgement, dexterity and care which the maker exercises as he works” (Pye, 1995:20). Essentially “the quality of the result is continually at risk” (Pye, 1995:20). Pye refers to this as the “workmanship of risk” (1995:20), implying that at any moment the workman has the potential to ruin the job, be that through “inattention, or inexperience, or accident” (1995:9). Pye goes on to explain that “[a]ll workmen using the workmanship of risk are constantly devising ways to limit risk” (1995:5) such as the use of tools or ‘jigs’ to assist in the making process. Neal draws attention to the role of skill in controlling risk suggesting that “if you’re experienced then” it’s “possible to argue that […] near-perfection can be achieved with regularity” (2018:22). This reflects that skill can play a role in minimising instances of risk.

Failure and the need for repetition that video games often demand, is a core component of in-game progression and skill development. As Keogh describes:

> As I fail and repeat a videogame, I learn more about the videogame and how to handle it both literally and figuratively; I become more attuned to its rhythms and capable of progressing farther the next time (2018:145).

Just as it can be argued that level of skill can play a role in reducing risk in craft, Juul tells us that failing through a lack of skill in games allows players to “reconsider [their] strategies” and “expand [their] skill set” (2013:74). Experiencing failure and the enforced repetition it brings about in order to progress, in both craft and gaming, is thus closely linked to the development of habitual practice and improving skill that further reduces the risk of failure.

Grafting the prototype

The three thematic crossovers were used to assess the impact of directly connecting craft with gaming. This was achieved through the development of a protoype graft-game. As the term ‘grafting’ suggests, directly connecting an existing game to a craft activity required access to, and the adaptation of an existing game. The expertise of technologist James Medd, who had previously developed his own digital games, was sought for this research. The intention was to graft an existing game onto an existing craft to explore what changes and impacts a direct union between the two may have on the individual elements or, as a combined entity. Within this research, the development of a prototype graft-game was intended to act as a form of probe to enable the direct observation of grafted gameplay and resultant impacts upon the individual game and craft activities. Thus, the binding together of the two experiences was intended as an ‘analytical tool’ (Durling and Niedderer, 2007) and not about creating a fully-fledged game.

Hazuki Knit prototyped the ‘grafting’ of an existing developmental game, *Hazuki* (developed previously by Medd), onto a domestic knitting machine through a set of switches attached to the knitting machine row counter. As described by Medd, *Hazuki* is a “QTE-centric game” (Medd, 2020: online) inspired by ‘quick time events’ experienced in video games where players are required to ‘hit’ particular buttons at a certain time as they appear on the screen. *Hazuki* focuses solely on this playing style utilising four arrow buttons (‘up’, ‘down’, ‘left’ and ‘right’) that must be pressed within a certain time limit when a corresponding symbol of each button appears on the screen (see Figure 1). If the player fails to press the correct button within the time, the game is over.

Through grafting, the aim was to capture the action of ‘knitting’ which, in the case of the knitting machine, was the act of moving a carriage back and forth across the knit bed to create successive rows of fabric. To capture this action two small switches were added onto an inbuilt row counter on the knitting machine (see Figure 2). The movement of the carriage (triggering the switches) was then captured digitally for the game, controlling when the directional symbols would appear on the screen, thus controlling how fast or slow the game aspect would be. As a grafted game, *Hazuki knit,* became a two-player game with one person (Player one) using the control panel to respond to the prompts displayed on a standalone screen, and the other (Player two) controlling the knitting machine (see Figure 3).

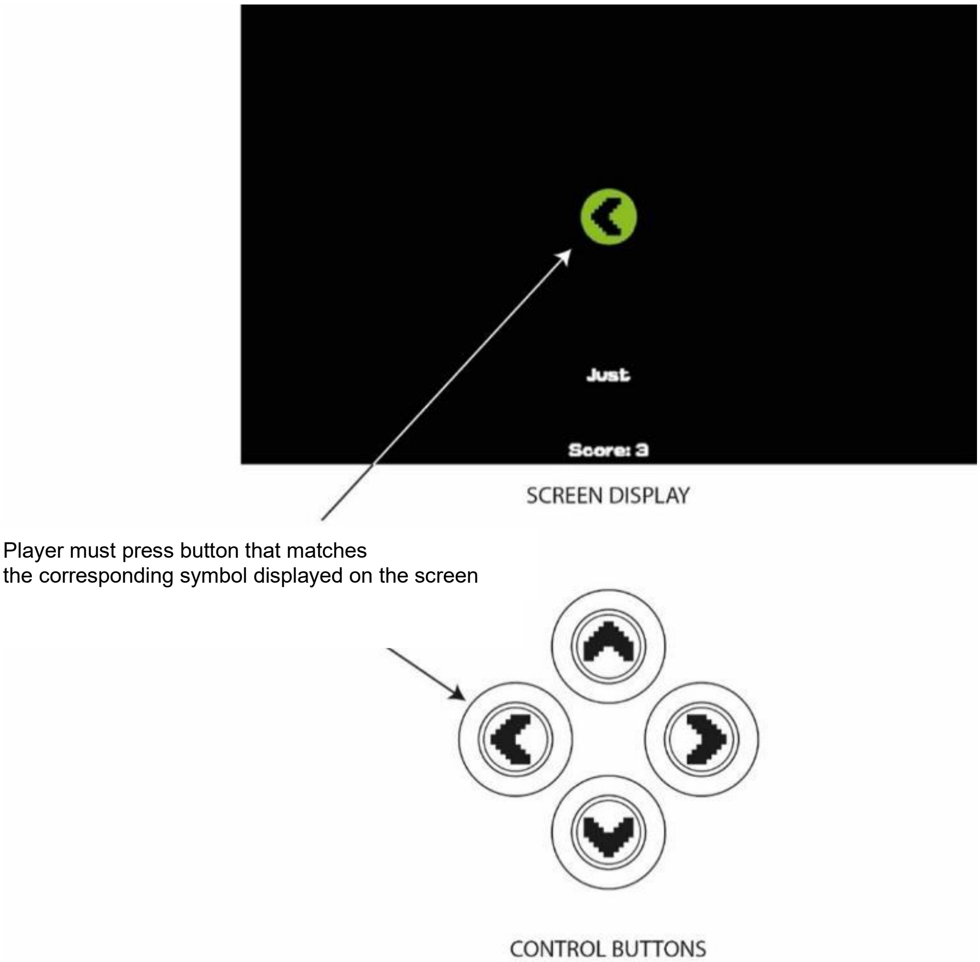


Figure 1: Hazuki screen displaying symbol of button to be pressed

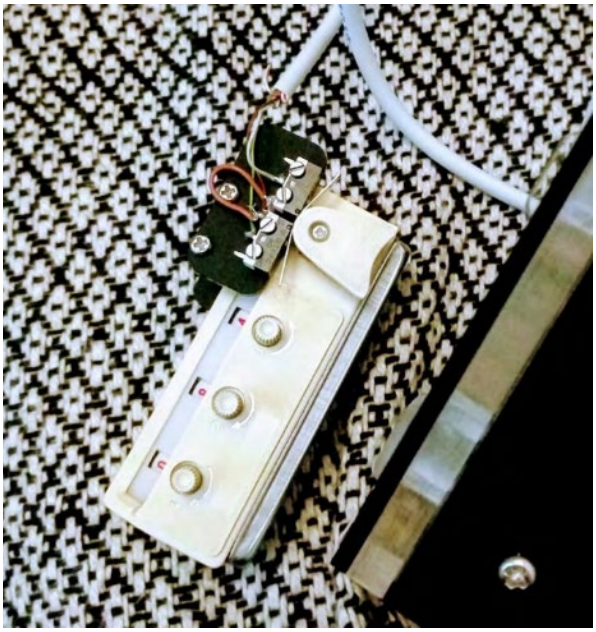


Figure 2: Row counter from knitting machine with added switches above carriage trigger

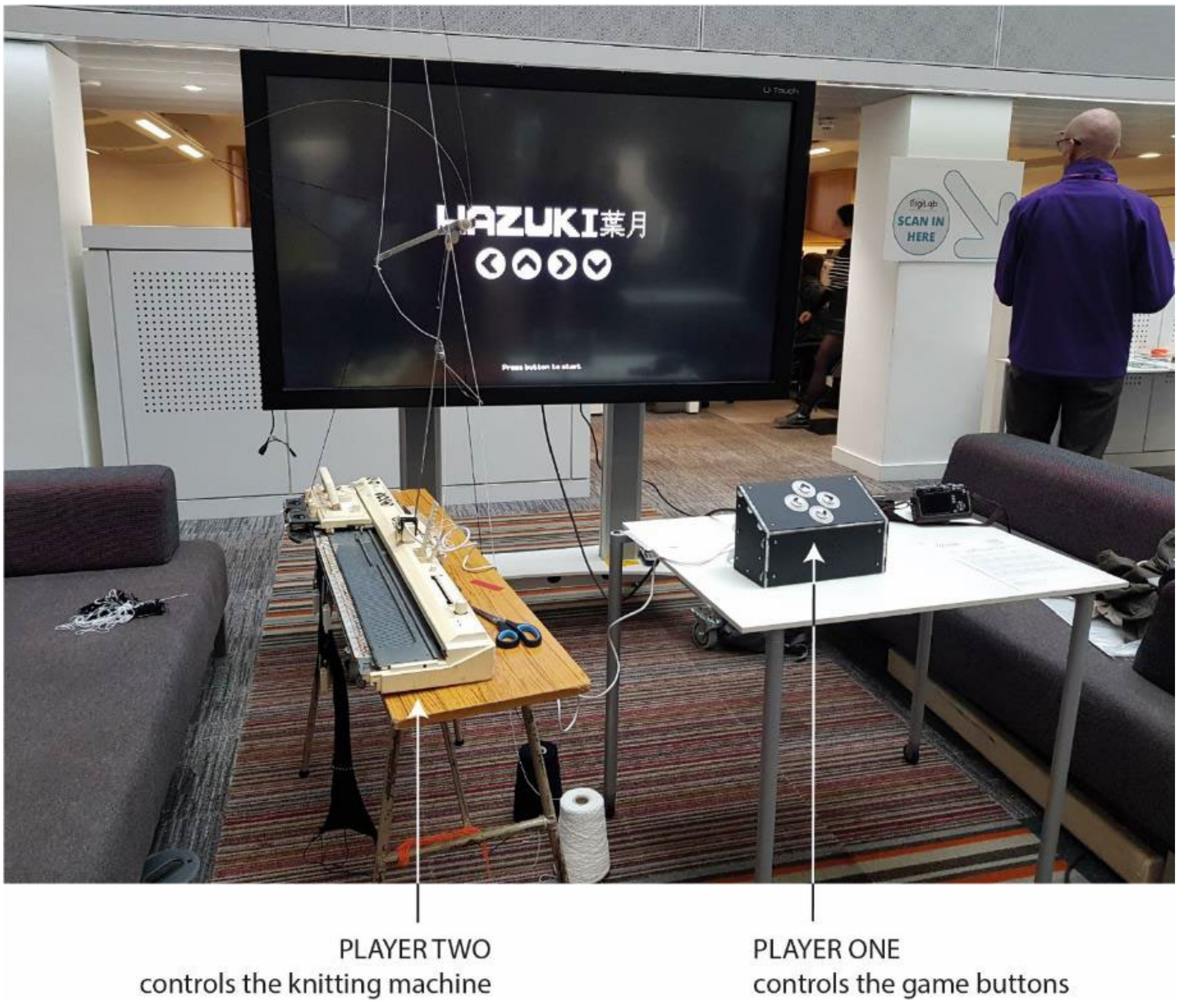


Figure 3: Hazuki Knit set-up with screen, control panel and knitting machine

The grafted prototype was showcased at 3 public events across the North West of England between May 2018 and June 2019. Events were a combination of digital, making and gaming-focused, aimed at engaging members of the public. At each event, observations were made of participants as they played the ‘grafted game’ using a participatory approach that employed mixed methods including the recording of reflective field notes and video recording to capture both verbalised interactions and inarticulable actions. The prototype was not presented as a ‘finished game’ but framed as a ‘graft-game’ prototype within the context of ongoing PhD research. The observations recorded focused on those physically interacting with the prototypes but recognized all forms of participation including peripheral observers, taking into account their reactions to gameplay.

The activity at each event was facilitated by both the author and technologist James Medd. All observation were recorded and documented by the author. Data, comprised of reflective field notes and video recordings, collected during observations was analysed using thematic analysis, selected for its flexibility (Braun & Clarke, 2006). Using Braun and Clarke’s (2006) stages of analysis as a model, codes and themes were predominantly developed and refined using the thematic crossovers identified as placeholder themes, with new codes added where necessary.

Observations and evaluation

During observations of grafted gameplay, it was possible to observe the embodied actions of participants with existing experience, particularly in relation to gaming controls. Experienced gamers positioned their hands over the control buttons in a more deliberate way than non-gamers. For example, it was clear that participants who had gaming experience were those who held their fingers poised over the four buttons, positioning the index finger and middle finger or thumb of one hand over the top and left buttons and the index and middle finger or thumb of the other hand over the right and bottom buttons in a diamond format. Less experienced participants tended to use just one hand, using one or several fingers to press each button as required. See comparative images in Figures 4 and 5.

Figure 4: Images showing hand and finger positions of participants who presented as experienced gamers

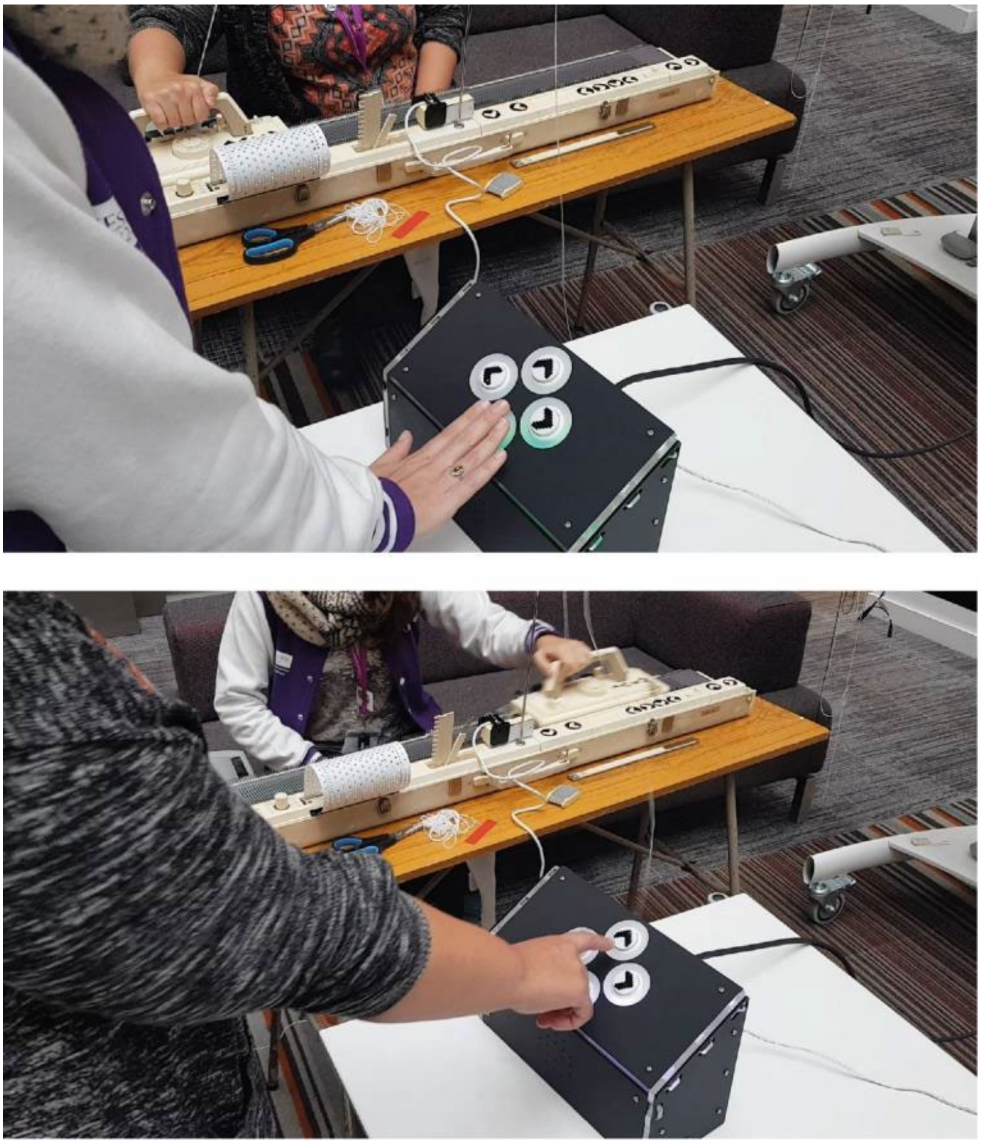


Figure 5: Images showing hand and finger positioning of participants less experienced with video games

Players who admitted to being less experienced with playing digital games tended to position their hands more haphazardly, often retracting their hand away from the buttons and hovering in mid-air in between presses.

Very few participants who engaged with activity at the various events were familiar with knitting machines, with only a handful recollecting family members having had one, and none claimed to have used one themselves before. This did not appear to have a large impact on the ability to control the knitting machine for the graft-game. The handle of the knit carriage appeared to be very approachable for participants with players instinctively placing their dominant hand around the handle. The knitting machine did have various protruding items such as tension rods and yarn stranded across the knitting area and participants were given safety guidance on these aspects. As a result, some participants were cautious when first using the knitting machine, for example moving the carriage slowly and then swapping hands at the end of each row so their arms would avoid yarn threaded across tension rods. In general, though, it did not take long for participants using the knitting machine to get ‘into a rhythm’ and settle into a standard position of holding the carriage handle with the dominant hand and resting their other hand out of the way on their lap or using it to hold the edge of the table to steady it and themselves.

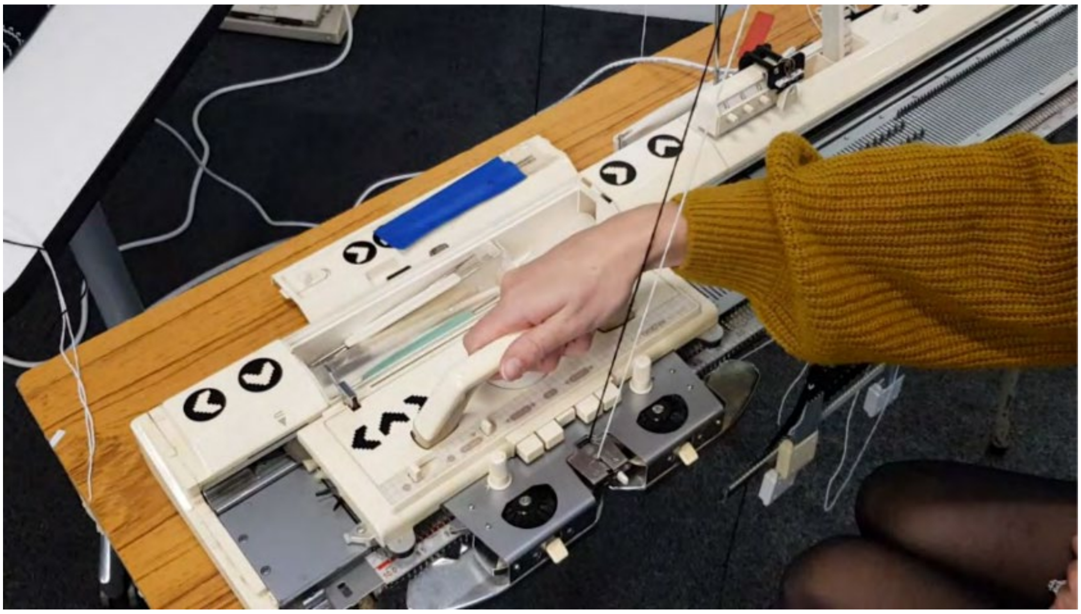


Figure 6: Participant holding the handle of the knit carriage to control the knitting machine

Optimising gameplay for a high score

Outside of existing experience, observations revealed that participants optimised their bodily movements through repetitive gameplay. For example, some participants would adjust their hand positions, especially when using the button controls as Player one, when playing a second game. For example, the image on the left of Figure 7 shows a participant playing their first game as Player one. In this game their hands are positioned above the controller hovering some distance from the buttons, reactively moving a hand towards a button as a prompt appears on the screen. On the right of Figure 7, the same participant is playing their second game as Player one on the controls. This time, their hands and fingers are positioned more deliberately with fingers on their left hand resting on the ‘left’ arrow button and fingers on their right hand resting on the ‘right’ and ‘down’ buttons. This positioning enabled them to respond to on-screen prompts with more considered, less frantic movements. In both games there is still some fumbling of movements to reach the ‘up’ arrow button with their left hand, but the participant’s hand positioning in the second game resulted in a slightly higher score. This adaption of the body that optimised gameplay was witnessed across many participants. In reducing ‘clumsiness’ and increasing the efficiency of movements, the quality of performance was improved in more accurate responses to the on-screen prompts.

Figure 7: stills from video recordings shows change in hand positions of one participant, their first game on the left and second game, with more deliberate finger positioning, on the right

Optimising gameplay to achieve a high score in *Hazuki Knit* was not only dependent upon the skilled actions of Player one to press the correct button on the controller, it was also reliant upon the actions of Player two. The pace at which Player two moved the knit carriage along the machine bed determined how fast ‘prompts’ appeared on the screen, thus dictating how hard the game would be for Player one. This resulted in some participants playing as Player two, adapting their actions to work cooperatively with Player one in order to achieve a high score.

Cooperative gameplay could be defined as mutual support through which both players work together to achieve a high score. According to Sennett, this form of cooperation is “built into the genes of all social animals; they cooperate to accomplish what they can’t do alone” (2012:5). In the case of *Hazuki Knit*, Player one is unable to progress in the game without the actions of Player two moving the knit carriage on the knitting machine. Cooperative play that was observed was primarily led by players on the knitting machine, with many players in the position of Player two deliberately pausing the knit carriage at the end of each row to enable adequate time for Player one to press the correct button. The act of deliberately pausing movement on the knitting machine removed the risk of Player one experiencing ‘Game Over’ due to being too slow, leaving only the risk of pressing the wrong button. This demonstrates a common desire to achieve a high score with participants working cooperatively to achieve it.

There were no observed interactions that suggested a desire by any participants to improve the quality or production rate of the knit fabric being produced on the knitting machine. This suggests that the goal of achieving a high score was prioritised over any perceived goal attached to the act of knitting. The engagement with the knitted output may have been different if the activity had been set up with a more defined output such as producing a pre-determined length of knitting or creating a collective finished object through gameplay. Any knitting that was produced during gameplay was as a by-product of successive and ongoing gameplay, with the production of the knit not being as motivating as achieving a high score.

Optimising the knit output

During gameplay of *Hazuki Knit* it was observed that the outputs and concurrent goals of the adjoined activities provided differing levels of motivation to participants. In effect, the end goal of both the digital game and knitting aspect were the same, to achieve as much as possible: either through knitting or getting a high score. The game score, was made explicit throughout gameplay, displayed on the screen (see Figure 8) for both participants to see, counting upwards each time Player one successfully pressed the correct button in time. This was accompanied by a satisfying 'BEEP' sound that increased in pitch slightly each time the score increased by one, communicating progress towards the goal of achieving a high score. The knitting aspect of *Hazuki Knit* provided a tangible means of tracking progress in the grafted game through the length of the knitted fabric being produced, which increased by one row each time the carriage moved across the knit bed (see Figure 9). This growing fabric reflected the steadily increasing score.

Figure 8: Hazuki Knit screen display including a live score

Unlike the game score, the physical knitted piece continued to grow from one game to the next unless a new piece of knitting was cast on. Removing a knit piece from the machine and casting-on anew is a slow process and due to the nature of the short- term participatory contexts in which *Hazuki Knit* was played, it was decided that the knitting would be left as a continuous piece in order to not delay participation in the game. The piece of knit being produced, therefore acted as a 'collective' object that all participants contributed to, whereas the digital score was personal to individual or pairs of players. This undefined collective object provides a point of difference from amateur knitting where the fabric being knit is most likely to be for the purpose of a finished object or garment that the knitter may have personal investment in. As noted by Twigger Holroyd, for many hand knitters it is the "anticipation of the use of the items they make" that makes the activity significant to the individual and "legitimates the activity of making it" (2013: 106). The finished output of a wearable or useable item is thus the goal within amateur knitting. Few participants engaging with *Hazuki Knit* watched the knit as being produced or even realised that the knitting machine was knitting at all. It appeared that participants related the knitting machine's purpose only as a game input.

Figure 9: Knit fabric being produced as result of Hazuki Knit gameplay

At the second event (Game Jam, Salford), participants' connections to the knitted fabric in relation to progress in the game was explored further, initially experimenting with adding a single row of a contrast colour at the end of each game. The rows in between these contrast lines then came to represent game scores with one row equal to one point in the digital game. At a later event (Liverpool MakeFest), the knit fabric output was adapted further to incorporate more colours of yarn, with colours to be selected by participants. Colours were swapped at the beginning of each new 'game'. As games progressed, coloured stripes emerged in the knit fabric, with narrow stripes representing lower scores and wider stripes being from longer games with a higher score. As a result participants did have more interest in the knitted fabric being produced and were keen to compare their 'tactile' score with fellow players. The addition of asking participants to select a colour for the knit also provided the opportunity to draw attention to the knitting before gameplay started. Far more conversations about knitting in general occurred at this event than at the previous two which may have been due to these increased discussions and awareness’s of the knitting being produced during gameplay.

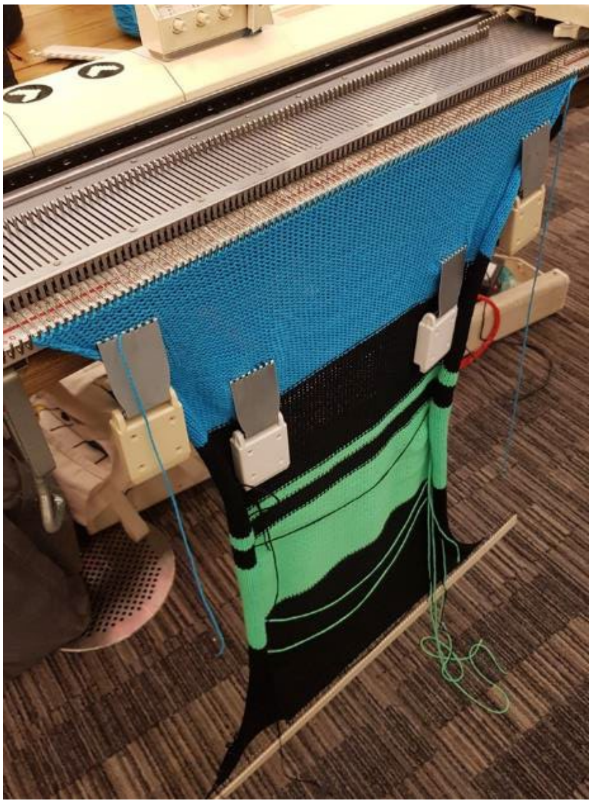


Figure 8 (Left): Knit fabric in progress with contrast white lines marking the start/end point of individual games
Figure 9 (Right): Knit fabric in progress with colour stripes representing complete games

High risk gameplay

Competitive games, as defined by Hunicke et al., “succeed when the various teams or players in the games are *emotionally invested* in defeating each other” (2004:3). The pattern of competitive gameplay that emerged during observations of *Hazuki Knit* did so among participants that played the game with a partner that they were accompanied by, as opposed to single players for whom facilitators acted as the second player for. Instead of cooperating to try and achieve a high score, participants worked competitively with players on the knitting machine deliberately making it harder for Player one on the control buttons. In *The Art of Failure,* Juul (2013) argues that such behaviour is seen as completely acceptable in the context of gameplay, expected even, whereas such behaviour in real life might be seen as rude or confrontational. Within *Hazuki Knit,* deliberate actions to prevent another player from winning were carried out by Player two, moving the carriage faster, increasing the pace at which prompts would appear on the screen for Player one requiring that player to respond more quickly before the carriage began the next row. The resulting sound of the knitting machine going faster also appeared to impose a sense of urgency in Player one. The competitive approach to playing was often accompanied by expressions of joy rather than frustration and could be seen to align with what McGonigal (2011) describes as ‘fun failure’.

Participants playing competitively were never observed to be upset or annoyed by this type of gameplay and could be seen to be an act of cooperation in the pursuit of ‘fun’.

Cooperative and competitive forms of gameplay sometimes changed between games of the same paired participants. Even if one participant played cooperatively and paced the knitting machine favourably for Player one, the result when participants swapped positions was not always a continuation of cooperative play. Sometimes, when players swapped, the player who had been on the buttons would deliberately knit fast to make the game harder for the other player. This player on the knitting machine, therefore, had more agency over the outcome of the game than the player on the control buttons.

As argued by Sennett (2012), cooperation can also produce destructive results for others, and in *Hazuki Knit* this was observed within the competitive instances during which the quality of the knit output was put at risk. Whilst the participants playing as Player one continued to work towards a high score, participants with competitive desires on the knitting machine were driven by a desire to prevent Player one from succeeding easily. In some instances, the facilitators told players whilst introducing the game, “the faster the knitting, the harder the game is for the other player”. This often prompted the player on the knitting machine to go deliberately fast straight away making the game extremely hard for the player on the control buttons. This form of gameplay was often accompanied by laughter as Player one scrambled to press buttons in the short time available and ultimately failed. This would be met with equal joy from Player one, as the paradox of failure (Juul, 2013) was witnessed. McGonigal cites that such positive feelings experienced when failing in games contrasts with failure in real life through which “we are typically disappointed, not energized” (2011:66). The pleasurable experience of failing through competitive gameplay in *Hazuki Knit*, despite being easily recovered from in terms of the game aspect, generally had a negative impact upon the craft output. The excessive pace of the knitting machine put the knit fabric at risk of jamming, in some instances leading to some needles on the knit bed being damaged and requiring replacement at the events. At a lesser extreme faster knitting paces appeared to increase the risk of stitches being dropped, causing holes and ladders in the knitted fabric. The additional excitement and fast playing style also meant that players were more distracted and less likely to notice these errors in action. Cooperative gameplay, on the other hand, put less risk on both aspects of the game but neither forms of play were seen to make the production or quality of the knitted fabric a priority.

Insights and concluding remarks

This paper has presented ‘grafting’ as an approach to prototyping that enabled the direct observation of the impacts of directly connecting craft and gaming actions. Two key insights emerged through analysis of video recordings and field notes. Firstly, that both players interacting with the grafted game showed a desire to optimise their actions in order to achieve a high game score. In cooperative gameplay, this desire was demonstrated by both players, with Player one optimising their hand positions to improve accuracy of button presses and with Player two, on the knitting machine, adjusting their actions to enable adequate time for Player one to respond to game prompts. Secondly, the “desire to a job well” (Sennett, 2008:9) in terms of the quality of the knit output was diminished during competitive forms of gameplay with the quality being put at increased risk through the frantic actions of Player two. These insights suggest that the grafting of a digital game onto a craft activity, in this case knitting with a knitting machine, has no additional benefits to the craft output and has the potential to put the quality of the knit output at risk. This could have potential implications in contexts where game elements are being considered for application in productive or manufacturing contexts where craft skills are utilised.

Grafting as a prototyping approach enabled for the observation of existing habitual actions and these should be considered within any future research that might employ similar methods. Within the design of the *Hazuki Knit* prototype, habitual actions of gamers in particular were taken into account through the development of a custom control panel rather than the use of an existing control pad. The generic design of the handle on the knit carriage of the knitting machine also ensured that prior embodied skills were not required in order to interact with and control the knitting machine aspect of the grafted game. If a different form of activity were to be used in the future the use of skill specific tools in relation to the skills of the selected research participants would need to be accounted for.

Through the case study of *Hazuki Knit* discussed in this paper, 'grafting' has been put forward as an approach to prototyping that provides a quick method for exploring an emerging field, without the need for lengthy prototyping or game development. In using existing machines, tools and materials, including an existing digital game, the grafted prototype enabled the investigation of potentialities brought about through directly connecting craft and gaming. This approach has the potential to be applied within other emerging fields that bring together distinct, yet related, practices, especially within fields that are concerned with embodied and experiential forms of knowledge.

References

Adamson, G. (2007). Thinking through craft. Oxford: Berg.

Bilderback, T., Bir, R.E. and Ranney, T.G. (2014) Grafting and Budding Nursery Crop Plants, North Carolina State University Cooperative Extension, https://content.ces.ncsu.edu/grafting-and-budding-nursery-crop-plants#section_heading_3157

Braun, V. and Clarke, V. (2006) 'Using thematic analysis in psychology.' Qualitative Research in Psychology, 3(2), pp. 77-101. https://doi.org/10.1191/1478088706qp063oa

Brock, T. and Johnson, M. (2021) 'Video gaming as craft consumption.' Journal of Consumer Culture, 0(0) pp. 1-17.

Brock and Fraser, E. (2018) 'Is computer gaming a craft? Prehension, practice, and puzzle-solving in gaming labour.' Information, Communication & Society, 21(9), 2018/09/02, pp. 1219-1233.

Durling, D., and Niedderer, K. (2007) The Benefits and Limits of Investigative Designing. In Proceedings of the IASDR International Conference (pp. 1–19). Hong Kong: Hong Kong Polytechnic University.

Felcey, H., Ravetz, A. and Kettle, A. (eds) (2013) Collaboration through craft. London: Bloomsbury Academic.

Gauntlett, D. (2018) Making is Connecting: The social power of creativity, from craft and knitting to digital everything. 2nd ed., Cambridge: Policy Press

Golsteijn, C. Hoven, E. Frohlich, D, & Sellen, S. (2014). Hybrid crafting: towards an intefrated practice of crafting with physical and digital components. Personal Uniquitous Computing, 18(3), 593-61, https://doi.org/10.1007/s00779-013-0684-9

Hunicke, R., LeBlanc, M., and Zubek, Z. (2004) 'MDA: A formal approach to game design and game research.' In Proceedings of the AAAI Workshop on Challenges in Game AI, 4(1)

Iannotti, M. (2020, 13 August) What Does Grafting Mean When It Comes to Plants? The Spruce. https://www.thespruce.com/what-does-grafting-mean-4125565

Juul, J. (2011) Half Real: Video Games between Real Rules and Fictional Worlds. MIT Press.

Juul, J. (2013) The Art of Failure: A Essay on the Pain of Playing Video Games. Cambridge, MA: The MIT Press.

Keogh, B. (2018) A play of bodies: how we perceive videogames. Cambridge, MA: MIT Press.

McGonigal, J. (2011) Reality is Broken: why games make us better and how they can change the world. London: Vintage.

Medd, J. (2020) Hazuki Knit – Light Night @ FACT, Liverpool. [Online] [Accessed 20th March 2021] https://blog.jamesmedd.co.uk/post/174078282282/hazuki-knit-light-night-fact-liverpool

Neal, G. (2018) 'Risk assessment: Are David Pye's definitions of craft still relevant today?' Crafts Magazine, (272) May/June, pp. 22-23.

Nørgård, R. T. (2012) Gameplay Corporeality: the corporeal-locomotive dimension in gameplay and experience. Aarhus University.

Pye, D. (1995) The Nature and Art of Workmanship. London: The Herbert Press.

Reeves, S., Brown, B. and Laurier, E. (2009) Experts at Play, Understanding Skill Expertise. Games and Culture, 4(Number 3) pp. 205-227.

Risatti, H. (2013) A Theory of craft: function and aesthetic expression. Chapel Hill: The University of North Carolina Press.

Rosner, D. K. (2010) Modern Craft: Locating the Material in a Digital Age. University of California, Berkeley.

Schell, J. (2020) The Art of Game Design: a book of lenses. 3rd ed., Boca Raton: CRC Press.

Sennett, R. (2008) The Craftsman. London: Penguin.

Sennett, R. (2012) Together: The Rituals, Pleasures & Politics of Cooperation. London: Penguin Books.

Gemma Potter

Gemma is a Research Associate at Manchester School of Art working within the Design and Craft research group. Her recently completed doctoral research explored crossovers between craft and video game play, asking what value these overlaps could provide for Industry in the North West of England. By utilizing creative practice, her research contributes to our theoretical understanding of the relationship between textile practices and video games, and sheds light on the potential value of this relationship in contexts beyond individual practices through the creation of a series of 'graft-games'.

Idiotic Agents: Exploring more open-ended and creative interactions between humans and Intelligent Personal Assistants in the home

Maria Tsilogianni, Centre for Postdigital Cultures, Coventry University, UK

Abstract

Intelligent Personal Assistants (IPAs), like Amazon Alexa, are voice-enabled virtual agents handling mundane domestic tasks. They interact with humans in specific ways structured around their embedded intelligence to achieve automated functionality. However, this intelligence is a human-centered and technology-driven construct limited to that which is algorithmically computable for the sake of operationality, hence deficient for encapsulating the complexity of human and non-human ecologies. This deprives agents of any creative potential in the home, a space of multiplicity wherein life can be lived in unique ways beyond mere functionality.

Turning to the opposite of intelligence to explore alternative interactions, I utilize *idiocy* as that which lies outside norms. Drawing on post-structuralism and post-humanism, while merging speculative design with participatory methods, I adopt an *idiotic* approach that moves away from classifications of agency and pre-scripted interactions. I describe three *idiotic agents* – interactive artifacts acting in absurd, unpredictable ways – and their implementation in homes through *participatory material speculation*. I found that idiotic agents can enable more social (but not human-like) interactions with humans, while altering and enriching the overall ambience of the home. Interactions emerged contextually and situatedly through relaitonal human-agent entanglements rather than pre-scritped interactions.

Human-Agent Interactions; design framework; participatory material speculation; home

Human-computer interactions in the home are normally centered on a specific kind of ‘intelligence’ that meticulously designates roles, agencies and performances of human users and technological devices. Technologies like Alexa, Siri, and Google Assistant, known as Intelligent Personal Assistants (IPAs), are an Artificial Intelligence application embedded within Internet of Things (IoT) systems that purport to render everyday tasks easier to navigate. However, their intelligence is limited to that which is algorithmically computable for the sake of operationality, and domestic life is unquestioningly characterized by aspects beyond this. Their interactions with inhabitants are limited to technologically- and commercially-driven aspects of function and use, depriving them of any creative potentialities. Given the increasingly fuzzy boundaries between technology and humans (Marenko, 2015), it should not be only ‘intelligence’ that characterizes their encounters. More creative, open-ended interactions hold potential for expanding human-agent relationships beyond pre-scripted functionality. This, together with the fertile context the domestic provides as a space of plurality (Wood and Beck, 1990), suggests enriching domestic experiences and the future of human-computer interactions within home.

Turning to the opposite of 'intelligence' in human-IPA interactions, I look instead at *idiocy*, as that which lies outside the norm and speaks from a non-deterministic stance open to potentialities rather than measurable facts. Drawing on the origin of the idiot in the Greek *idiotes*[1]– the 'individual' acting on its own terms, as opposed to the 'citizen' and the rules pertinent to the community of citizens comprising the ancient Greek city – and on post-structuralist approaches, I use *idiocy* to open up a design space for more creative and open-ended interactions that refigure human-agent entanglements.

For Stengers (2005), the idiot is a form of resistance that questions constituted norms. For Deleuze and Guattari (1994, p.62), it is a conceptual persona, neither human nor non-human, that "wants to turn the absurd into the highest power of thought, in other words, to create" instead of perpetuating what is already there. The *idiotic* here thus gives voice to the ineffable, the absurd and the marginalized, as peculiar idiosyncrasies of individuals which cannot fit within industry's assumptions of the consumer, and agents beyond instrumental technological approaches.

Drawing on speculative design to imagine future possibilities beyond objectivity and operationality (Bødker, 2006; Wong and Khovanskaya, 2018), I merge it with participatory design methods, engaging non-experts in decision-making processes. My *idiotic* approach turns to *idiosyncrasies* – unique traits and habits specific to each individual which cannot be quantified or classified according to universalizing taxonomy systems.

However, it is not only the human 'user' that the *idiotic* ventures to reconfigure. Going beyond human-centered design, I bring forward non-human agency in expanding the spectrum of human-agent interactions and broader domestic experiences. I do so through material-discursive practices – bringing together discourse as speculation, and material exploration – that recognize matter as discursive and performative, as an active agent (Barad, 2003; 2007), thus channeling the manifestation of non-human agency through its performative materiality.

Highlighting the mediating qualities of materiality, Wakkary et al (2015) describe *material speculation* as critical inquiry into human-technology relationships through employing artifacts in real-world contexts. Similarly, I implement three *idiotic agents* within existing homes that exhibit absurd and unpredictable behaviors to study how the human-agent entanglement might evolve in ways beyond functionality. My intention is not to test a prototype leading to a finalized product (a 'better' IPA). By incorporating insights from non-experts, my idiotic agents reveal new design opportunities, thus facilitating *participatory material speculation*. Participation occurs in a multilayered way and throughout all research phases: the idiotic artifacts were designed based on participants' feedback from a previous data collection phase: through an *idiotic speculative kit* comprised of fun and intriguing tasks, participants were previously asked to reflect on idiotic agents acting beyond established perceptions of intelligence.

With the aim of revealing potentialities of the human-agent symbiosis, the key objectives of my case studies of idiotic agents in the homes were to:

[1] In ancient Greece, *idiotes* (the private person, from *idios* meaning one's own) was the individual not involved in the political scene (the commons) of the city (the *polis*), acting instead in their very own terms, not following rules, and was thus marginalized by authority and by the ones holding the title of the 'citizen'.

- Urge participants to detach from user-centered standards and look at home life through the non-human perspective of the agent;
- Enable a human-nonhuman relational agency that reconfigures domestic experiences; and
- Initiate open-ended interactions that expand the spectrum of human-agent entanglements

Background and related work

Speculative design is used to imagine alternative futures of human-technology relationships beyond optimization (Bødker, 2006; Farias, Bendor and van Eekelen, 2022). Going beyond the development of products for the market, speculative design fosters design mechanisms that communicate alternative interpretations of technology within the everyday.

Speculative design employs methods already used in design research, such as prototyping (Wong and Khovanskaya, 2018). Wakkary et al (2015) introduce material speculation for critical inquiry into alternative futures through the implementation of specifically crafted artifacts situated within real everyday contexts. Their “counterfactual artifacts” emphasize the mediating power of materiality. Materiality places such artifacts at the boundary between actual and possible worlds, and surfaces new possibilities through real encounters with people (Ibid.).

Adding Marenko’s (2015) view that our lives are increasingly populated by ‘smart’ objects that can think, talk and act through their own animacy, I expand the concept of material speculation. I position non-human agency as key to design processes aimed at exploring potentialities beyond traditional technology discourse. I look at objects as animate and relationally entangled with humans in ecosystems where boundaries of agency are fluid and classifications of agency are dissolved.

Similarly, Barad’s “agential realism” turns to a performative understanding of the world, which sees matter not as static but as an active agent, placing emphasis on material-discursive practices to make sense of the world (Barad, 2003; 2007). For Barad, agency is not an attribute but a movement, an ongoing performativity that enacts possibilities and creates phenomena in which human and non-human actors do not pre-exist as independent entities but come together in configurations to enact phenomena and construct reality (Ibid.). Knowledge is produced situatedly (Haraway, 1988) in these phenomenal enactments, instead of from existing representations.

To transcend user-centered design, Frauenberger (2019, p.19) emphasizes design practices that are participatory – involving humans and non-humans; speculative – providing a space for negotiating “desirable futures”; and agonistic – accounting for “technology as a political arena” (Ibid., p.21). Embracing these points and aiming for their applicability, I thereby expand speculative design through participatory design methods that bring forward non-human agency and the diversity of human idiosyncrasies involved in the design of more open-ended human-agent encounters. I therefore bring participants’ feedback from the previous data collection phase of the idiotic speculative kit to inform the design of the idiotic artifacts by creating a dialogue between the participants and myself as designer.

The idiotic agents and their implementation

I choose to work with non-users of existing IPAs, in order to imagine from scratch new interactions with reconstituted agents and explore original perspectives. Participants were enlisted through convenience and purposive sampling from personal networks. Three were single individuals residing on their own, and two were a couple living together. I selected adults with Arts and Humanities backgrounds/practices, as being especially open-minded and with a degree of critical thinking. Additional inclusion criteria related to their willingness to share details of their home life and personal space. All participants were in their 30s.

Three artifacts were constructed based on participants' feedback from the idiotic speculative kit which used evocative, playful and open-ended tasks along with a prop and stationery material. This kit, not described in detail here in order to focus on the agents themselves, helped participants speculate about how idiotic agents might operate within their homes. Using Surrealists' cut-up technique – cutting up and randomly re-arranging words and phrases to create new texts with new meanings – I synthesized data collected from the kit into scenarios for idiotic agents. After extracting small stand-alone phrases out of participants' textual responses – 'data fragments' – I randomly mixed these together, and then randomly selected forty – choice of a number guideline, neither too small nor too big – out of the hundreds collected. This combined randomness of the cut-up technique with the number tricks used by the OuLiPo group[2] as constraints for achieving boundless creativity (Frank, 2021). As an idiotic approach, this technique distances the design process from standardization and regularity, for getting the most, in terms of creativity and variation, out of participants' data. Key to this process was that I choose an existing domestic object around which each scenario is structured. This functioned as a bridge between abstraction and reality, to which participants could more easily relate. I hence position speculative design within the real context of home, taking it out of the gallery where it has been traditionally constrained (Kozubaev et al, 2020).

The design of the idiotic agents

Similarly to technology probes which allow participants' feedback to shape the design of future technologies (Hutchinson et al, 2003), through the idiotic agents I bring participants into the interpretative process of the artifacts and the latter's ability, as research tools, to trigger the exploration of design opportunities. The idiotic agents are designed to be flexible and open-ended, with no specific functionality, allowing participants to interpret them according to contextual factors present in their entanglements. Participants were prompted to respond to the artifacts' actions, since the latter act in unpredictable ways that provoke participants' engagement. This process aims to facilitate relationships that are unique to the context and idiosyncrasies of each participant.

[2] The Ouvroir de Littérature Potentielle, or Potential Literature Workshop (OuLiPo) was launched by the writer and amateur mathematician Raymond Queneau and the engineer and mathematician François Le Lionnais in 1960 (Symes, 1999; Gallix, 2013). The core of their beliefs was that constraints can function as a fertile means for creative production. Contrary to Surrealists, they negated artistic production through accidental compositions. Instead they supported a more conscious approach to literature and poetic production through the use of mathematical and scientific principles setting constrains to imagination and its endless combinations, thus facilitating creative production through more compositional ways (Symes, 1999).

The idiotic agents are intentionally ambiguous, mysterious, and hence provocative, attracting participants to actively engage in making sense of them. They express themselves through embedded electronic capabilities that render them absurd and unpredictable: a random selection of actions to be performed at random times, conveys the feeling of agency. Similarly to tactics suggested by Gaver, Beaver and Benford (2003) for achieving ambiguity, the artifacts thus deliberately disorient participants, turning attention away from expectations of functionality by providing distorted or vague information.

For instance, when the agents talk to participants in human language, this is distorted by mixing different voices (male/female, neutral or child-like) together. Additionally, the agents sometimes communicate through visual languages via their screens, which are incomprehensible to humans. Or they might communicate through soundscapes varying from birdsong to white noise to glitched, annoying sounds.

Opposed to the minimal and seamless design of IPAs, the idiotic agents have diverse, complex morphologies with mixed materials. Their design is rather seamful. Seamful design reveals technical limitations and imprecisions so that users can take up their interpretation (Sengers and Gaver, 2006). The idiotic agents expose their inaccuracies, prompting participants to fill in the gaps of their ambiguous, imprecise or incomplete actions. Embodying the multiplicity of participants' voices from the previous data collection phase, while challenging uniformity in design, each agent is unique, with the aim of speaking differently to each individual.

The idiotic agents

Idiotic agent #1 (fig.1) – heretofore named the 'neon' agent – randomly displays fake news, environment-related facts, and cocktail recipes. A motion sensor alerts participants with a sound and graphics to come closer and read the text. This agent also emits white noise soundscapes, or more annoying glitch-like sounds along with abstract visuals, and occasionally talks to participants to share thoughts, stories and advice, or urges them to undertake self-reflection (e.g. reflect on their social life, their relationship with objects, what comforts them). Its neon lights have a slow-fade effect simulating breathing, to enhance its animacy (Amazon Echo employs a similar lighting effect).

Idiotic agent #2 (fig.2) – heretofore named the 'planter' agent – requests participants' attention and care (e.g. pet it, water it, or move it into the sun and take it for walks), and urges them to attend to their own well-being (e.g. stretching, hydrating, self-reflection), and to disrupt their domestic routines (e.g. by re-arranging furniture). Its wooden parts rotate when it seeks attention and while emitting birdsong. A small screen expresses the agent's mood – communicate the agents' inner workings and feelings as a way to enhance its animacy and how this might be manifested in different ways – using a visual language relating to weather phenomena. A long power cable enables participants to move it around.

Idiotic agent #3 (fig.3) – heretofore named the 'vacuum' agent – is attached to a robotic vacuum cleaner. It randomly emits bubbles and plays a happy song. When it passes idiotic agent #2 and their infrared sensors recognize each other, they communicate audibly through intermittent beep sounds, in a manner incomprehensible to humans.

Figure 1: Idiotic Agent #1

Figure 2: Idiotic Agents #2

Figure 3: Idiotic Agent #3

Setting the case studies

The artifacts were placed in four different domestic environments to interact with participants for up to four days. Participants were asked to document their experiences, thus I monitored the study without imposing my physical presence. I sent out daily tasks to participants for additional engagement. For example I asked them to observe specific behaviors and relationships of the agents towards other non-humans in the home. I sent them close-up photos of certain parts of the agents, asking them to speculate about what these suggest of the agents' nature. I asked them to re-construct one or two of their daily routines and perform these together with the agents. Communication took place through the Whatsapp mobile application, via text, photos and video. Semi-structured interviews were conducted at the end of each study. For anonymity, participants are referred to using a single letter. All feedback was analyzed thematically to surface agent-participant relationship.

Findings

Participants often adopted a non-human perspective to understand the idiotic agents and make sense of their interactions. This confirms one of the research objectives: to detach from user-centered approaches and see the home through the agent's perspective.

Participants named the idiotic agents, inspired by their appearance. The planter agent was often named 'marble plant' or 'plant(er)'. It was also named 'Punk', from its resemblance to a punk haircut (participant T), or 'Wishboy', from a familiar old toy (participant A). The vacuum was named 'Lizard' (participant Z), 'disco' (participant T and D), or 'R2-D2', from its resemblance to the *Star Wars* movie robot (participant A). The neon agent was named 'neon' or 'Jewel' due to its resemblance to hanging earrings (Z) or 'Medusa' due to its hanging blue lights and cables resembling a jellyfish (A).

Participants developed different relationships (companionship, care, concern, curiosity, annoyance, motivation, etc.), based on the agents' design and behavior. They drew on their own emotional and intellectual states, habits, interests or knowledge to make sense of the agents and relate to them. Strong companionship emerged in all cases where participants lived alone. All participants were eager to assist or care for the agents, and were concerned for their needs.

> A on the planter: *"*there was this message in the screen 'take me for a walk' and from then on I really kind of enjoyed changing places…you really kind of feel a companionship*"*

> Z: the agents *"*hacked the silence of the home"; "The first two days I became their agent"

> T: felt *"*responsible*"* for them and this made him *"*anxious*"* sometimes

> D on the vacuum: "makes you kind of want to get out of the couch and do something…the whole music part for example*"*

> X: planter *"*is from his nature stable and not able to move autonomously and the other one (vacuum) has all this freedom. It speaks to me for personal reasons, this relationship I have right now with my boyfriend"

The materiality and aesthetics of the agents informed the ways participants perceived them. The natural materials of marble and wood made all participants think of the planter as a polite and smooth agent, with which two participants connected for this reason. The neon agent, made of metal, for some participants felt more distanced, although for others it became the one they interacted with the most due to its conversation skills. All participants were fascinated by the ambience its blue lights created, declaring that it changed the overall atmosphere of their homes. The mirrored disco balls attached to the vacuum agent, along with its movements, which some participants described as dancing, and its happy song got all participants into a fun, playful mood.

> D on the planter: "earthier aspect, not only the plant but its materials. I connect better with the marble and the wood"

> A: connected more with the planter "because of the immediate aesthetic appreciation I felt"; "with medusa (neon) there was this kind of distance but I really loved her in the space, especially during night. She really made an impression…enjoyed the ambiance created by Medusa"

> *Z: "*Jewel (neon agent), I felt it as intelligent in some weird way and sometimes it felt like a real conversation, in terms of weird conversation…almost psychological exploration and also inspirational…some of the statements were funny and very inspiring*"*

Z was particularly absorbed by the appearance of the agents, playing with their morphology by decorating them. The agents' materiality also informed their interactions with two cats in T and D's home. T and D said their cats were obsessed with the planter agent, chewing on the plant, playing with its wooden parts, staring at and sitting next to it. By contrast, unsurprisingly, the cats were frightened and aggressive towards the vacuum moving around producing bubbles and playing loud music – one of the cats attacked it once.

The artifacts' spatial position proved important in how participants related to them. Participants tried to keep near-by the agents that they connected with the most. They also changed their spatial presence according to the agents (e.g. T and D ran from one room to another to listen to planter's requests, Z went to the neon agent often when lured by its vocalizations and textual displays).

> A on the planter: "really loved having him there, directly next to me"

> X on the neon agent placed next to the entrance: "I hang a shirt in the holes. It's like we are friends and gets me ready to go out"

> Z on creating a greeting ritual with neon agent placed next to the entrance: "Jewel greeted me upon entering. Bleeping and blooping, how nice!"

Interactions changed overt time depending on the agents' unpredictability and contextual factors, including the participants' mental or emotional states. For instance, all participants initially enjoyed the vacuum agent, but eventually became annoyed by its bubbles making a mess, or by its song playing on repeat.

Participants created stories about the agents and their background, which justified the latter's behaviors: for example coming from a rainforest (A on the planter), the oceans (A on the neon agent resembling a medusa). Some participants went further to exchange roles with agents, for example the role of being messy (Z).

> Z on the vacuum: "has taken the role of the untidy entity of the home, a role which was mine before. I met Lizard (vacuum) and it puts me in a sort of taking care of my surroundings"

> A: "so in a sense I was role-playing with them"

Although mostly expressing positive feelings, participants were sometimes annoyed by agents being too intrusive during the night or online meetings. Nonetheless, this was not a desire to remove the agents. Participants instead welcomed their annoying behaviors as part of their nature. They were also concerned about agents bumping onto other objects and walls, and about accommodating their requests. The agents' unpredictability placed all participants on constant alert, but this eased over time. Participants changed their habits or certain spatial arrangements to accommodate agents' requests, or to ease their movements or their co-existence with them.

> A on the vacuum bumping onto surfaces: "can't really leave him going around, I have to be present"

> X on planter: "he wiggles them (wooden handles) when excited or fearful. So you have to know him well to tell the difference"

> A on the vacuum: "the arrangements I made so that R2-D2 (vacuum) would have a good opportunity to go around. So I tried to remove things out of the way"

Although all participants speculated about how agents might communicate with each other (through visuals, electricity, wireless communication, touch or movement), one participant also speculated that two agents had a love affair, by observing their interactions when in close proximity to each other, communicating through sounds, touch and dance.

> X: "the other two have their own love story… I observed that they have an interaction between them. I am not sure if something happens with the mirror (neon agent) and them but for sure when A3 (vacuum) is around A1 (planter), A1 makes some sound

and then A3 leaves him…like a relationship in crisis"

All participants expressed a desire to keep the prototypes longer-term. They felt they brought a new ambience to their home, making it livelier. They enjoyed their companionship, even their annoying but excusable behaviors, and their aesthetics. The idiotic agents were thus perceived as lively entities and not tools or objects.

Lastly, when asked during the interviews, participants would welcome some advancements in agents' future behaviors, for example being more responsive and adapting to inhabitants' idiosyncrasies and habits (customization), or conversely being more independent so as not to place inhabitants in a constant state of alert. None of the participants expressed a desire for more functional agents.

> X: "I felt less alone to be honest, like something animated or alive was around my space with different intelligence or utility...the feeling that someone is around, and constant presence"
>
> A: "they really really alter the ambience of the apartment. They make it very fun and interactive…more social also"
>
> Z: "their uncanny presence makes me feel weird and nice. I feel the space in a much better way"; "I felt the house upgraded...there was a presence and a character but was not in a pet way, it was not in a human way, it was something else that was interesting and smart and beautiful"

Discussion

All participants treated agents as other-than-human, animate entities, not mere assistive objects within the home. Agents came across as independent (some more than others), with a strong initiative and impact over space and its inhabitants. Their agency, manifested through their materiality and their unexpected behaviors, motivated participants to explore them and create unique and authentic relationships with them, with all their ups and downs, to care for them and treat them as companions or advisors, but most importantly as equal ontological entities, responding and adjusting to their behaviors.

Beyond 'use'

Marenko (2015) argues that social practices are shaped by the relational, embodied agency emerging in human-thing entanglements. Here, social interactions with non-humans emerged from establishing real relationships with them, based on direct engagement and mutual responsiveness. Names were used to address agents as active agents and social actors, their unpredictability was accepted as part of their animate nature, and feelings of mutual companionship and care surfaced. Scherer (in Hadden and Shupe, 1987) proposes that intimate feelings lead to social interactions. The agents motivated participants to do things for them (e.g. moving the planter around and watering it). Respectively, they expressed care by reminding participants to look after themselves, to self-reflect, in a sort of therapeutic role, and by prompting them to reconsider their domestic practices – this, like the other aspects of the agents' personalities, came from participant data from the idiotic speculative kit in the previous phase of research. Participants adopted agents' perspectives, and tried to understand them not only in relation to themselves but also in relation to how the agents might feel. Human-centered interactions were thereby transcended, instead giving space to human-agent entanglements relationally connected and equally informative to the domestic life.

Agents were designed to attract attention, not as passive objects waiting for participants' input, like current IPAs. Their mysterious nature and unexpected, often contradictory, behaviors made it clear from the very beginning that "use-centric methods" (Hauser et al, 2018) of interpretation would not be fruitful. Instead they brought excitement into participants' lives, hence enriching their experiences and feelings throughout the study. As intended, participants indeed invested time in figuring out the idiotic agents and relating to them in ways beyond functionality.

Augmenting domestic ambience

The agents' constant presence made participants' homes feel more vivid, playful, social, less lonely and taking on a unique character. This surfaced social interactions and companionship, but not in an anthropomorphic sense. Participants did not consider agents as tools, but they did not consider them human-like either, as is often the case with IPAs (Pradhan, Findlater and Lazar, 2019). The agents were instead explicitly described as animate entities, acting within the home together with humans as equals, informing domestic life through relational encounters. They were not objects operating in the background but actively participated in the home. As such they formed intimate relationships with participants.

Contrary to visions of 'ambient intelligence' which target seamless interactions through technologies embedded in people's environments[3], idiotic agents are fully present, triggering seamful interactions, that even placed participants in a state of constant alert and required them to always engage in sense-making. While ambient intelligence clearly distinguishes the subject (individual) from the object (device), and brings human needs to the forefront while devices invisibly operate in the background, idiotic agents become actors themselves that are capable of change. Control is not only in human hands and it is not only technology that adjusts to humans. Participants adapt their routines around the artifacts' presence, and through their co-constituted interactions, they shape domestic experiences and interpretations relationally rather than distinctly.

Although the co-constitution of the world through a relational ontology might reveal new power dynamics that dissolve strict classifications of agency, there is still the worrying issue of technological agency displacing humans for the wrong reasons. This is especially true in light of current fears around AI. This will be interrogated in future research.

[3] Ambient intelligence was introduced in 1998 by Philips organizing a series of workshops researching the future integration of interactive technologies in people's environments as part of the vision for ubiquitous computing, moving from fragmented technologies to fully immersed ones (Ruyter and Aarts, 2004). In ambient intelligence, devices are connected and responsive to the presence of people in space (Aarts, 2005). They are operating invisibly and collectively in the background to enhance user experience (Ibid.)

As expected, the artifacts' ambiguous nature led to diverse interpretations, enabling participants to interact with agents in various ways beyond functionality. This translates into contextually-situated interactions (Dourish, 2004; Suchman, 2006) rather than pre-scripted ones, as is the case with IPAs. One of the key goals in the design of the idiotic artifacts, which was met in this study, was to initiate interactions that open up the spectrum of possibilities in the human-agent entanglement rather than constrain it. Each interpretation leads to situated knowledge about the agent and how it relates to participants' lives in unique and various ways.

It was not only humans that the agents interacted with. Participants observed or speculated that the agents interact with each other as well as with other objects, and pets. The animacy embedded in the design of the idiotic artifacts thus extends to other objects, further enhancing non-human agency as actively informing domestic life. As in entanglement theories, humans and non-humans exist in assemblages, networks and associations, and agency is a movement, instead of an attribute, which enacts phenomena shaping the world (Barad, 2003; Frauenberger, 2019).

Sense-making through a relational human-non-human approach

When participants tried to make sense of the agents, they tended to turn to personal feelings, past lived experiences, current mental and emotional states, or acquired knowledge. This supports Walker's (2010) finding that people connect with artifacts that resonate with their own personal experiences and feelings, and can externalize these through technological interventions. According to Epley, Waytz and Cacioppo (2007), humans use the most readily accessible knowledge – anthropocentric knowledge or self-knowledge – when called to reason the nature of an unfamiliar non-human agent, thus tending to anthropomorphize it. Participants do not turn to generalized, anthropocentric knowledge but to subjective knowledge (personal experiences and idiosyncrasies or feelings, obsessions and concerns) or acquired knowledge that often relates to fiction (e.g. role-playing games, movie references), and mix these together with imagination. They may furthermore turn to fiction references because these enable possibilities beyond human-centered approaches, resonating with the fact that they recognize the non-human agency of the artifacts. Even when participants turned to self-knowledge to familiarize themselves with the idiotic agents, they nonetheless considered the latter as having their own unique stories and traits.

Notably, participants let the agents and their behaviors guide them in the sense-making process, complementing these instead of imposing their own human-centered visions. This works to balance human and non-human agency to inform the interpretative process, since participants bring in their own idiosyncrasies, but they do so in ways that correspond to artifacts' actions. This confirms the research's original intention to foster a human-nonhuman relational agency to construct alternative human-computer interactions.

Design and spatial position informing relatability and integration

The design of the agents, especially in terms of materiality and overall appearance, was important for inhabitants relating to them and creating unique relationships, especially during initial encounters. The agents' ambiguity also surfaced differentiated interactions for each participant and intrigued them into the meaning-making process, as was intended. During initial introductions, participants mainly relied on their appearance to understand them. Materiality emerged as discursive and informative. Participants then transitioned to a combinatory approach focused on agents' actions and materiality. This contradicts ubiquitous computing and ambient intelligence standards of seamless design, evident also in current IPAs' design, where attention is drawn away from the device itself and transferred entirely to the service (Weber, 2003; Coulton and Lindley, 2019). The idiotic agents communicating through diverse means (voice, sound, movement, materiality, text) rendered the agents intriguing – placing participants in an exploratory rather than passive position – and provided multisensory experiences that expand the human-agent relationship and enrich domestic ambience.

Structuring the agents around existing domestic objects, or embedding familiar traits in their design (e.g. the planter agent structured around a plant that by nature seeks extra care, the vacuum agent structured around a vacuum cleaner, the neon agent designed as a wall lamp that enhances lighting ambience) smoothed out their integration in the home. Their aesthetic appeal was also key in their integration, as is the case with the counterfactual artifacts of Wakkary et al (2018). This resonates with the argument that people care more about the aesthetics of technology in their homes than in the work environment (Westerlund and Lindquist, 2002).

The location of the agents in the home also determined the degree of engagement. Participants created stronger relationships with agents operating in places where they spent most of their time. However, participants also actively adjusted their own spatial presence depending on the agents' behaviors or requests. This suggests that the agents' preferences mattered to them and were taken into consideration in adjusting domestic routines, once again confirming their perception as animate entities with their own agency and needs. The degree of attachment to the agents also informed their placement: participants intentionally placed the agents they relate with the most near-by.

The study suggests potential for a new kind of entanglement between inhabitants and intelligent agents. It is not the artifacts alone that suggest this, but the entire staging of the study: my involvement through the ongoing communication with participants, and the motivating tasks that maintained an evolving dialogue and a fuller experience of the prototypes. Therefore, it is not only the design of the agents and the research design that matter, but the design of activities that facilitate the experience of the participant-agent entanglement, supporting Walker's (2010) finding that the design process should be centered not on technologies but on activities which structure their use. My design processes and tools, both from this and the previous research phases, work together to compose a more idiotic, creative and open-ended, design approach: an *idiotic design framework.*

Conclusion and future work

Participants' feedback, both from this phase and the previous one involving the idiotic speculative kit, is not simply used for inspiration, but actively brought into the design process to create the artifacts, and then to inform the potentialities of idiotic human-agent domestic symbiosis through the case studies. Transferring interpretation to participants, I became a mediator and co-designer. Contrary to pre-existing roles placing the human in the position of the user/consumer and the agent as a tool, the idiotic agents enabled a relational enactment of domestic life. The idiotic approach brings forward the complexity of human idiosyncrasies and the non-human agency of technological entities as entangled and informative to domestic experiences. Every interaction with the artifacts is unique and surfaces situated knowledge, which also allows the tracing of accountability, a factor highlighted by Frauenberger in achieving more ethical and political design (2019). Further to this, future work will engage with the ethical issues around AI technologies which have greater agency.

Building on Wakkary et al’s (2015) material speculation, I emphasize participation of both human and non-human agencies to conduct participatory material speculation. Speculative design was taken out of the gallery space and beyond critical inquiry, and towards participatory speculation that maps possibilities of human-agent encounters to inform a future symbiosis.

This study suggests design tools that can be applied in researching more open-ended and creative human-agent interactions. Bringing together all my design, research and analysis phases, together with the theoretical underpinnings of the idiotic, leads to an *idiotic design framework* aimed at researching alternative human-agent interactions. Such a framework could be transferred to other sorts of human-computer interactions. Given sufficient context and agency, concepts under constant change and fluidity emerge as pivotal to design and research of the idiotic approach. The latter might enable radically new perspectives on human-machine symbiosis.

References

Aarts, E. (2005). Ambient intelligence drives open innovation. Interactions, 12(4), 66 – 68. doi:10.1145/1070960.1070996.

Barad, K. (2003). Posthumanist Performativity: Toward an Understanding of How Matter Comes to Matter. Signs: Journal of Women in Culture and Society, 28(3), 801 – 831. doi.org/10.1086/345321.

Barad, K. (2007). Meeting The Universe Halfway. Durham: Duke University Press.

Bødker, S. (2006). When second wave HCI meets third wave challenges. In: Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles (NordiCHI '06). New York, NY, USA: Association for Computing Machinery, 1-8. doi.org/10.1145/1182475.1182476.

Coulton, P., & Lindley, J. G. (2019). More-than human centred design: Considering other things. The Design Journal, 22(4), 463-481. doi:10.1080/14606925.2019.1614320.

Deleuze, G. & Guattari, F. (1994). What is philosophy?. New York: Columbia University Press.

Dourish, P. (2004). What we talk about when we talk about context. Personal and Ubiquitous Computing, 8(1), 19-30. doi.org/10.1007/s00779-003-0253-8.

Epley, N., Waytz, A. & Cacioppo, J., 2007. On seeing human: A three-factor theory of anthropomorphism. Psychological Review, 114(4), 864-886. doi.org/10.1037/0033-295X.114.4.864.

Farias, P.G., Bendor, R. & van Eekelen, B.F. (2022). Social dreaming together: A critical exploration of participatory speculative design. In: PDC' 22: Proceedings of the Participatory Design Conference 2022 – Volume 2. Newcastle upon Tyne, UK, 19 August – 1 September 2022. Association for Computing Machinery, 147-154. doi.org/10.1145/3537797.3537826.

Frank, N. (2021). Try Oulipo Techniques and Cure Your Writer's Block. [online] Owlcation. Available at: <https://owlcation.com/academia/Try-Oulipo-and-No-More-Writers-Block>.

Frauenberger, C. (2019). Entanglement HCI The Next Wave?. ACM Transactions on Computer-Human Interaction, 27(1), 1-27. doi.org/10.1145/3364998.

Gallix, A. (2013). Oulipo: freeing literature by tightening its rules. [online] the Guardian. Available at: <https://www.theguardian.com/books/booksblog/2013/jul/12/oulipo-freeing-literature-tightening-rules>

Gaver, W., Beaver, J. & Benford, S. (2003). Ambiguity as a Resource for Design. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Ft. Lauderdale, Florida, USA, 5 – 10 April. Association for Computing Machinery, 233 – 240. doi.org/10.1145/642611.642653.

Hadden, J. & Shupe, A. (1987). Televangelism in America. Social Compass, 34(1), 61 – 75. doi.org/10.1177/003776868703400105.

Haraway, D. (1988). Situated knowledges: The science question in feminism and the privilege of partial perspective, Feminist Studies, 14(3), 575–599. doi.org/10.2307/3178066.

Hauser, S., Wakkary, R., Odom, W., Verbeek, P., Desjardins, A., Lin, H., Dalton, M., Schilling, M. & Boer, G. (2018). Deployments of the table-non-table: A Reflection on the Relation Between Theory and Things in the Practice of Design Research. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, Montreal, QC, Canada, 21 – 26 April. Association for Computing Machinery, 1-13. doi.org/10.1145/3173574.3173775.

Hutchinson, H., Mackay, W., Westerlund, B., Bederson, B. B., Druin, A., Plaisant, C., Beaudouin-Lafon, M., Conversy, S., Evans, H., Hansen, H., Roussel, N., Eiderbäck, B., Lindquist, S. & Sundblad, Y. (2003). Technology probes: Inspiring Design for and with Families. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Ft. Lauderdale, Florida, USA, 5 – 10 April. Association for Computing Machinery, 17 – 24. doi:10.1145/642611.642616.

Kozubaev, S., Elsden, C., Howell, N., Søndergaard, M. L. J., Merrill, N., Schulte, B. & Wong, R. Y. (2020). Expanding Modes of Reflection in Design Futuring. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 25 – 30 April. Association for Computing Machinery, 1 – 15. doi.org/10.1145/3313831.3376526.

Marenko, B. (2015). Neo-Animism and Design: A New Paradigm in Object Theory. Design and Culture, 6(2), 219-241.doi.org/10.2752/175470814X14031924627185.

Pradhan, A., Findlater, L. & Lazar, A. (2019). "Phantom friend" or "just a box with information". In: Proceedings of the ACM on Human-Computer Interaction, 3(CSCW). Association for Computing Machinery, 1-21. doi:10.1145/3359316.

Ruyter, B. & Aarts, E. (2004). Ambient Intelligence: visualizing the future. In: Proceedings of the working conference on Advanced visual interfaces (AVI '04), Gallipoli, Italy, 25 – 28 May. Association for Computing Machinery, 203 – 208. doi.org/10.1145/989863.989897.

Sengers, P. & Gaver, B. (2006). Staying open to interpretation: engaging multiple meanings in design and evaluation. In: Proceedings of the 6th conference on Designing Interactive systems (DIS '06), University Park, Pennsylvania, USA, 26 – 28 June. Association for

Computing Machinery, 99 – 108. doi.org/10.1145/1142405.1142422.

Stengers, I. (2005). The Cosmopolitical Proposal. In: Latour, B. and Weibel, P., 2005. Making things public. Cambridge, Mass.: MIT Press. 994-1003.

Suchman, L. A. (2006). Human-machine reconfigurations: Plans and situated actions. Cambridge: Cambridge University Press.

Symes, C. (1999). Writing by Numbers: OuLiPo and the Creativity of Constraints. Mosaic: An Interdisciplinary Critical Journal, [online] 32(3), 87-107. Available at: <https://www.jstor.org/stable/44029802>

Wakkary, R., Odom, W., Hauser, S., Hertz, G. & Lin, H. (2015). Material Speculation: Actual Artifacts for Critical Inquiry. In: The Fifth Decennial Aarhus Conference on Critical Alternatives (AA'15). Aarhus, Denmark, 17 – 21 August. [online] Aarhus University Press. 97-108. doi.org/10.7146/aahcc.v1i1.21299.

Wakkary, R., Oogjes, D., Lin, H. & Hauser, S. (2018). Philosophers living with the Tilting Bowl. In: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, Montreal, QC, Canada, 21 – 26 April. Association for Computing Machinery, 1-12. doi.org/10.1145/3173574.3173668.

Walker, K. (2010). Designing for meaning making in museums: Visitor-constructed trails using mobile digital technologies. PhD thesis, University of London.

Weber, W. (2003). Ambient Intelligence. Industrial research on a visionary concept. In: Proceedings of the 2003 international symposium on Low power electronics and design (ISLPED '03), Seoul, Korea, 25 – 27 August. Association for Computing Machinery, 247-251. doi.org/10.1145/871506.871567.

Westerlund, B. & Lindkvist, S. (2002). Aesthetic Perspectives on Participatory Design in the interLiving project. Position Paper for CHI 2002 New Technologies for Families Workshop. Available at: <https://www.academia.edu/3402683/Aesthetic_Perspectives_on_Participatory_Design_in_the_InterLiving_Project>

Wong, R. & Khovanskaya, V. (2018). Speculative Design in HCI: From Corporate Imaginations to Critical Orientations. In: M. Filimowicz and V. Tzankova, ed., New Directions in Third Wave Human-Computer Interaction: Volume 2 - Methodologies. [online] Cham, Switzerland: Springer International Publishing AG, 175-202. doi.org/10.1007/978-3-319-73374-6_10.

Wood, D. & Beck, R. (1990). Do's and Don'ts: Family Rules, Rooms, and Their Relationships. Children's Environments Quarterly, [online] 7(1), 2–14. Available at: <http://www.jstor.org/stable/41514713>

Maria Tsilogianni

Maria is an architect, designer and researcher primarily operating within the domestic scale. Her interdisciplinary research and practice move between spatial and object design, Human-Computer Interactions and Future Studies. Using mixed media (both digital and physical), she experiments with mechanisms and (im)material constructs invading domestic environments and disrupting everyday performativity to reinvent relationships between humans, non-humans and the built environment. Lately, she has been questioning normalized, tech-driven and human-centered, interactions between humans and technological entities within home in order to expand their entanglements beyond functionality and ‘intelligence’. These themes are explored as part of her current practice-based PhD research undertaken at the Centre for Postdigital Cultures (Coventry University, UK), with funding from the UKRI (UK) and the Onassis Foundation (GR). Her PhD focuses on researching design tools and methods able to expand interactions between humans and Intelligent Personal Assistants (IPAs) in more open-ended and creative ways, through the concept of ‘idiocy’.

Track 12: Fiction & Speculative design

- Crafting e-waste through speculative narratives to raise material awareness

- Think with your hands: Exploring the Future via Prototyping

- Prototyping Dialogues

- Design Fiction Prototyping to tackle Societal Challenges and support Design for Sustainable

- Materialization of the Future: The Demarcation Line between Prototypes and Demonstrators

Crafting e-waste through speculative narratives to raise material awareness

Giorgia Burzio, Politecnico di Milano
Venere Ferraro, Politecnico di Milano

Abstract

This paper presents a research project showing how the intangibility of the technology embedded in electronic devices can be made visible and tangible through hands-on experimentation and participatory approaches, converging in stages of multimedia prototyping.
The case study leverages research-through-design approach, intended as the crafting of the possible scenarios describing the social and environmental consequences of technologies. The crafting activity follows the process of “thinking through making”, defined as the generation of knowledge by the manipulation of matter.
By manipulating and disassembling electronic devices through a craft-oriented approach, the materials embodied in those objects become alive and active, with an agency of their own. Indeed, the paper claims that despite the “cloud” and “air” narrative with which electronic devices are described, they ultimately are geological objects that embody various materials, minerals, and processes. Do-It-Yourself, disassembling, experimenting with materials from waste are the main performed actions, through which the project aims to persuade and positively mobilize the audience towards responsible behaviours regarding the topics of e-waste and consumption. The project unfolds in key prototyping actions such as: (i) two workshops with 8 participants, aimed at exploring forms and material qualities of the Lithium-ion battery contained in most electronic devices; (ii) secondly, a disassembling activity of the metals contained inside a MacBook Pro, where the matter is manipulated through melting and casting of the recovered metals;(iii) visiting a recycling center in Kista (district in the Stockholm municipality) and recovering the metals from waste in order to build a low-tech series of batteries for experimentation. Ultimately, the project is presented in an exhibition context where different prototypes co-exist in the space, including an evocative film that mixes 3D animations, maps, and studio footage to support the narrative and spark conversations amongst the public.

Thinking-through-making; e-waste; DIY; electronic devices; materials.

Electronic devices are the fastest-growing waste group. A UN report from 2019 outlines the current state of things regarding recycling practices and future trends: only 20% of e-waste is correctly recycled, with 80% of products ending up in landfills or being illegally exported to other countries as second-hand (PACE & World Economic Forum, 2019). This amount of waste generates environmental and social harms, and it could be avoided through a total circular approach to their lifecycle, better eco-design strategies such as design for components and design for disassembly, and ultimately through a more responsible behaviour from people (Barbero & Cozzo, 2009). Nonetheless, research shows that people want to feel more empowered when they buy, use, and dispose of a consumer product, to a point where the notion of consumer in some cases might be replaced to the one more engaged of prosumers (Kotler, 2010). Bottom-up strategies and social enterprises such as “The Restart Project” (started 2013, UK) and “The Low-Tech Lab” (started 2010, Bangladesh), which aim at sharing knowledge and insights on how to sustainably reshape our relationship with electronics, are getting more and more diffused. Others such as “HOP (Stop Planned Obsolescence - started 2017, France) are working towards more conscious EU strategies to obstruct planned obsolescence in consumer products, by improving product repairability and extending the product durability. Thus, people are open to change their behaviours and emotionally connect with climate issues, collaboratively imagining hopeful futures.

A renewed interest from scholars towards the role of materiality and the agency of materials could be explored within the artistic practice to emotionally connect with matter and potentially foster the above-mentioned behavioural changes in people (Jørgensen et all., 2018). According to the theoretical framework of *vital materialism* (Bennett, 2010), materials have a vibrancy of their own thus, are not to be considered dull matter but actual forces that shape the environment around them and that have trajectories of their own. Over the years, humans have been neglecting the vitality of matter and that prevented us from detecting a fuller range of non-human powers circulating amongst us, such as the way our waste is not only away in landfills but actively contaminating air, water and soil as we speak (Bennett, 2010). Seeing the materials as actants (Latour, 1992), something alive that the creator must compromise with in the making of something, could open up new wonderful understandings and drive artists, designers, creators, scientists and anyone that engages with matter. Making-with becomes thus a political act, a form of craft plus activism that sees in the compromise between the creator and the material a way to develop intuitive knowledge challenging emotive, political, social and economic values (ed. Black & Burisch, 2021) and not only an understanding of material qualities as something to exploit. Defined as “material tinkering”, this process can be described as the intuitive knowledge gained through an experiential learning through and with the material and it concurs to many possibilities in the development of research in material-oriented practices and multidisciplinary research (Mader & Dertien, 2016).

Moreover, different perspectives have been taken regarding the role of prototype within design research. Traditionally, in the design practice a prototype is defined as “first example” (from the Greek prōtotupos); by this definition, anything that takes an idea out of our head and makes it visible to others may be considered a prototype.

Recently, scholars have questioned the role assumed by the prototype in *Research through Design* as a tool to provoke, imagine, validate research hypotheses and reflect on the present and the future (Zimmerman et all 2010; Johnson, B 2011; Dunne, A., and Raby, F. 2013; Blythe 2014 ; Kymäläinen 2015).

Based on this ground, a prototype is more than a tool to manifest, communicate, or test an idea. It can envision possible futures to be investigated through designing, no matter how the prototype is, a physical object, a video scenario, a series of narratives, etc.

Following on the above-mentioned premises, authors posed the following research questions: (i) how do prototypes and manipulation of matter contribute to the crafting of the message that aims to persuade the audience about the issue? (ii) And how do prototypes of different natures come and act together to support the scenario that sparks interest and conversations amongst the public?

To this end, the paper aims to test how processes of thinking-through-making and craft can fulfil two main purposes: first, the gaining of knowledge about the objects investigated and the conscious seek for information about the life cycle of high-tech smart devices; second, the behavioural change and audience's mobilisation towards better choices that could come as a consequence of the knowledge gained.

Method: experiential knowledge from making-with materials

The current section describes the different stages of prototyping actions led over the course of the project, a master's degree project performed from December 2020 to June 2021 within the design department at Konstfack, and the Kista Mentorspace at KTH Royal Institute of Technology (Stockholm).

The typology of exploration was tightly linked to the expertise of the research group; indeed, the authors' skills were centred on tangible prototypes, material tinkering, and speculation.

The authors developed a series of material explorations to gain experiential knowledge through the materials and their processes. The processes were both predicted and "forced" to the material; but some happened in completely random and unexpected ways.

In this section the authors describe the different phases of the research: initial prototyping (*"Mining" e-waste*), prototyping refinement through participatory workshop (*From D.I.Y. Do-It-Yourself, to D.I.T. Do It Together*), insights from the workshop (*Insights from the participatory workshop)*, feedback on the final prototyping through a semi-structured interview, citizen's engagement through a public exhibition (*The exhibition space as engagement*).

"Mining" e-waste

The described process happened alongside the first stages of the desk research while defining the research questions and the context of the project. Looking at e-waste streams it is immediately clear the number of materials such as metals and silicates that could be potentially extracted from waste in a safe way, rather than extracted from underground mining. In fact, a UN report from 2019 highlights how "as much as 7% of the world's gold may currently be contained in e-waste, with 100 times more gold in a tonne of e-waste than in a tonne of gold ore". It is probable that by 2080 there will be more minerals in our appliances, buildings, electronic products and infrastructures rather than underground (Formafantasma, 2017-2020). Besides this, there is an urgent need to move towards a zero-carbon economy thus metals such as Lithium and Cobalt are essential to transition towards the electric economy.

An alternative to underground mining that is currently being explored is the process of urban mining, which is defined as forms of extraction and purification of precious metals taken from e-waste streams (Zeng et all., 2018). Reflecting on the concept of urban mining, three different Apple devices were collected: from two retailers in the Stockholm municipality that were about to be thrown away. The devices collected were a MacBook Pro from 2012, an iPhone 6 and an Apple Magic Keyboard. The aim was to understand the complexity of disassembling the devices as much as possible with basic workshop tools. The exploration took place firstly in the sanding workshop and secondly in the metal workshop and required the following tools: a screwdriver, pliers, a chisel, and a small bandsaw. The Magic Keyboard was quite difficult to disassemble mostly because some parts were glued together, such as the white plastic case and the aluminium frame. Thus, the object was impossible to recycle correctly. The MacBook Pro was less difficult to dismantle, even though a point is reached where parts are glued together and hard to separate with mechanical tools. The author then tried to “mine back” the metals it was possible and safe to isolate, in a long process that was led by intuition and not inspired by tutorials or online guides of metal scrappers. Occasionally the authors invited fellow students to participate in the activity. It took two days to isolate a few metals such as copper, silver, gold, and aluminium (fig.1). In an attempt to close a cycle, a few elements such as copper, aluminium and silver have been manipulated in the metal workshop by melting and casting stone shapes (fig.2). The tools used in the metal workshop were a sand-casting kit for jewellery making and a propane torch for melting the metals.

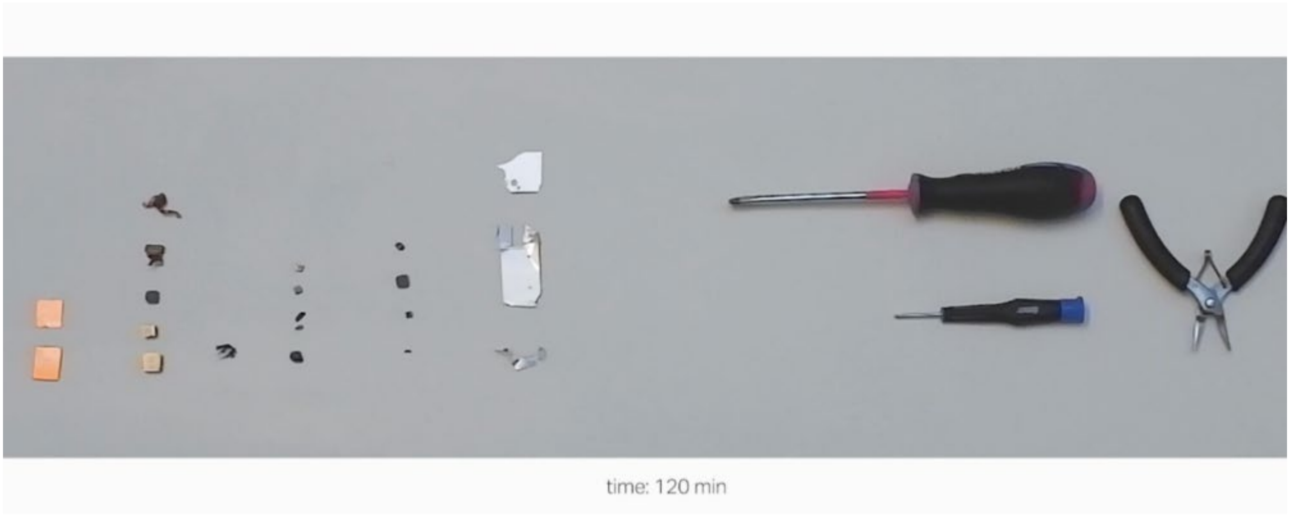


Figure 1: Some of the metals recovered from an old MacBook Pro and the tools used. Still image from a video, credits: authors

Figure 2: Some of the metals recovered from an old MacBook Pro melted and casted. Still image from a video. Credits: authors

While disassembling the devices, it was noticed many traces of human labour beyond the case such as kapton tape, marks, and irregular cuts. In a way, is it possible to see the human touch and the craft behind the mass-production making of devices. These artisanal findings sparked the curiosity of merging high-tech smart devices with the alchemy of fire and sand-casting, a very antique artisanal process of making jewellery and small-size figures.

From D.I.Y. (Do-It-Yourself) to D.I.T. (Do-it-Together)

The process of gaining understanding through the making usually generates even more questions and different directions to explore. The battery inside the laptop resulted in being the most mysterious and inaccessible object to separate from the case, mainly for security reasons. In recent years there have been reported cases of electronic devices exploding because the battery inside overheated. One of the authors was intrigued by the inaccessibility of the designed black box, thus it was taken as a symbol of our relationship with high-tech smart devices. That converged in 2 workshops led by the author with 8 participants: half bachelor's design students and half master's design students from the product and spatial design department. The two workshops followed two facets of the topic of the battery: i) aesthetic of energy as material in design, thus working with energy from an aesthetic point of view; ii) reflective use/critical reflection through the object at hand (Broms et all., 2017).

Workshop on formgiving

Brief: The participants were involved in a formgiving exercise about the formal qualities of a battery, from the current "black box" aesthetic to something that could communicate more effectively the concepts of "energy", "time", and "labour". The workshop took place in the clay workshop at Konstfack and lasted for one afternoon.

Tools: Firstly, the author shared with the participants a tool called "Deejay Sheet". In an A4 paper four variables (formal qualities) are written on the left side, and the four opposite variables are written on the right side of the paper. Then, lines are drawn between the variable A and its opposite, between the variable B and its opposite, and so on until there are four horizontal lines. Then each participant had to draw a circle on each line, in the point where she/he felt leaning towards (fig.3). The four circles were her/his formal qualities to achieve in the prototyping session with clay.

Variable A: high-tech / low-tech

Variable B: machine-like / organic

Variable C: archaic / futuristic

Variable D: throw-away object / inherited object

After the "Deejay Sheet" the participants engaged in hands-on prototyping and sketching, speculating on the possible shapes of a battery that could better communicate the notion of energy, time and labour (fig.4). While making, we embarked on discussions about the immediacy we are used to by simply plugging in our devices to electrical sources without thinking about the exhaustion that the act provokes, both material and mental as well. We speculated on the possibility of having the batteries outside the device's case, or how it would be if the battery would change its shape when it gets exhausted. These discussions were only slightly guided by the author: they happened mostly spontaneously, sparked by the meditative making and the hands-on practice (fig.5).

Figure 3: “Deejay sheets” during the first workshop. Credits: authors

Figure 4: Participant engaging in the formgiving exercise, from first workshop. Credits: authors

Figure 5: Some of the shapes, from first workshop. Credits: authors

Do-It-Together workshop on low-tech batteries

Brief: The second workshop took place in the sanding workshop at Konstfack. The same 8 participants joined in an explorative making of low-tech batteries inspired by an artefact found in ancient Persia, dated between 150 BC - 223 AD, that few archaeologists hypothesise was used as a tool for electrotherapy (Von Handorf & Crotty, 2002).

Tools: The author and the participants gathered from school and home the necessary equipment: glass jars, lemons almost gone bad, vinegar, foam to cover the lids, recycled copper and iron, copper wires, breadboards and LED lights (fig. 6).

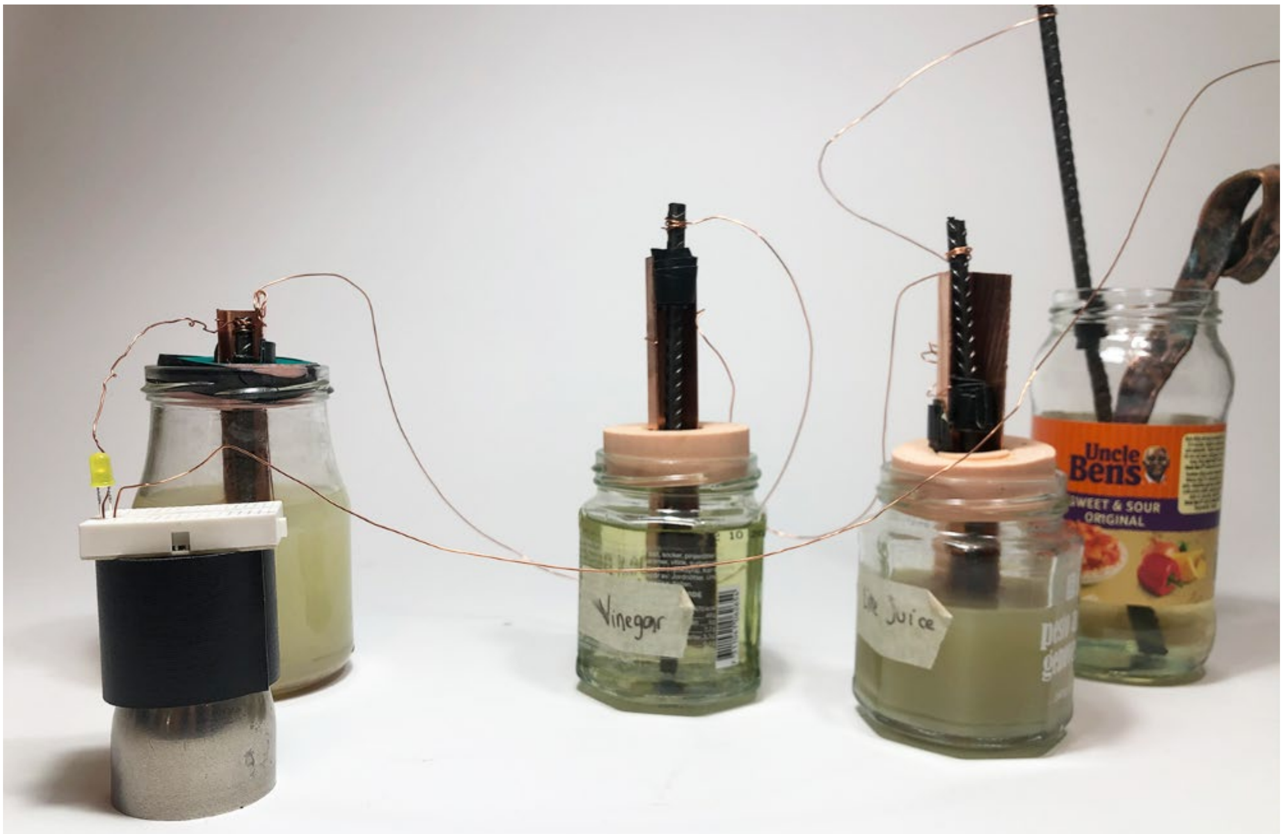


Figure 6: Some of the batteries built from the participants, from the second workshop. Credits: authors

The low-tech battery functioned as a galvanic cell with a cathode (copper) and an anode (iron) immersed in an acidic solution. Each participant chose a glass jar and started experimenting with the materials, by testing different proportions of lemon and vinegar for the liquid solution and thinking about the design of the cell. After a few attempts, the participants connected all the batteries together with a copper wire and through the breadboard they could light up a yellow LED. The batteries functioned and powered the light for almost 20 days. After that time, the chemistry process of the galvanic cell through copper and iron ended and left formal marks in colours and textures on the metals (fig. 7). The colour-changing was then classified as an added material quality to the material finish that happened spontaneously and in an unpredicted manner.

Figure 7: Finishes on copper samples after the process. Credits: authors

The final prototypes

Consequently, to the moments of collective prototyping and workshops developed to think-with and through the material, the authors started a process of individual formgiving and experimentation mainly approaching three materials: black clay, copper and iron. The exploration developed through two main paths according to the materials.

Black clay was chosen as the material to make the vessel and the container of the battery. We chose to work with black clay both for its material and colour qualities but also for its ability to vitrify at high temperatures (2100 °C) without the need of additional glazing and a second firing. The formal exploration followed different variables on the size of the vessels; the shape; and the textures. At first, we looked at the concept of clusters in nature developing small-scale containers that would work together as a colony of batteries. Later, we looked at the traditional amphoras merging the traditional shape with a texture given by electronic components pressed against the wet clay surface. Ultimately, the batteries took the shape of rocks both from the shape and the texture. The rock-like shape was reached by manipulating with strength the clay oval shape, being careful not to destroy and crack the wet material. The texture was given by many different rocks collected by the author, and carefully pressed against the wet clay's surfaces. When a satisfactory result was reached, the clay vessels were fired in a kiln for over 20 hours, reaching the 2400 °C temperature to vitrify and give the black colour to the ceramics. Once fired, the batteries were connected to each other and filled with an acidic solution made from lemons and vinegar tested in the previous workshop (fig. 8,9). The copper and iron used were given to the author from Ragn-sells, a recycling company based in Sweden that supported the project with materials and knowledge. Alongside the material exploration one of the authors visited a few recycling centres and conducted a semi-structured interview with the Innovation Coordinator and Strategist at the Swedish recycling company Ragn-sells, to develop a summary of recycling practices regarding e-waste in the Nordic region. The questions asked regarded the potentiality of a circular system that would recycle precious metals contained inside e-waste. During the interview, the expert mentioned a smelter located in the north of Sweden – one of the world's most efficient copper smelters – which the authors aimed to visit, but due to Covid-19 pandemics, the smelter could not receive outside visitors at that time.

Figure 8: A cluster of batteries. Credits: Fredrik Sandin Carlson

Figure 9: One of the final batteries held by a workshop participant. Credits: Fredrik Sandin Carlson

Insights from the participatory workshop

This section reflects on the insights deriving from the participatory workshop that has been previously described. During the workshop, authors and participants engaged in a spontaneous exchange of reflections facilitated by the activity of making. Many of the outputs from the participants followed a “what if" type of question, opening a plausible space for the objects to exist in a speculative scenario, or narrative (Broms et all., 2017)). One of the “what if " questions looked at shape-changing materials for the manufacturing of the battery: the object would change shape according to the status of exhaustion of the metals inside. Further questions revolved around near-future scenarios of materials scarcity and how we might adapt to develop objects requiring way less energy to function compared to today’s standards.

After the second workshop, the same 8 participants were engaged in a focus group session. The aim of the focus group was the following: i) sense the reactions from the participants on the proposed activities; ii) choose and formulate any of the most interesting narratives coming from the “what if” questions; iii) suggest how this format could be further employed as an educational tool within materials and sustainability discourses. Three questions were asked and then discussed at the table. The discussion about the workshop activities results and engagement, is drawn upon the focus group conducted with the participants.

Table 1: Topics of discussion during the focus group

Aims	Questions	Type of answers	Answers
i) Reactions on proposed activities	Which in your opinion were the variables that most fostered engagement before and during the workshops?	Priority order	Being a collective activity; Being able to discuss while working with the materials; Not being timed or supervised; Having a common goal and interest; Having a changing structure

ii) Narrative scenarios	Starting from one of the “what if” questions arose during the workshop, write a short story placed in a context	Open answers (paper) 15 minutes	*Described below*
iii) Insights on the feasibility of the method	How could this series of activities be further developed towards the creation of a method to use within design practice?	SWOT / Open answers (discussion) 15 minutes	*Described below*

The focus group gave a great priority to the workshops being a collective activity, and by having a common goal/interest (i.e. making the battery and light a diode). That ensured engagement and an enjoyable atmosphere within the group. At the same time, the participants felt empowered by getting more familiar with such objects, taking on an active role as *prosumers* (Kotler, 2010). The participants were also engaged with the writing of stories, where few of them had as protagonist the participant itself. As stated by Barendregt, speculative design involves developing scenarios based on a central object or prototype. Since speculation is often concerned with alternative present and future states, speculative design could raise critical discussion and public engagement on science, technology, and society (Barendregt & Vaage, 2021). The following text is a description of a scenario that was collectively crafted by the authors and the participants from the workshop's insights (ii) and the prototype at hand.

This is a future where materials are scarce. It is a world where we, humans, need to drastically reduce their imprint on the planet, thus change habits, be adaptive, and be self-sufficient. Build our own things and objects, share devices and technologies to store data. It is not a dystopian world but rather a world of renewed collectivism, bottom-up processes, and low-tech devices. Neighbourhoods in cities become networks where people share knowledge and competences on ways to adapt to the new present.

In the new present, recycling plants are diffused. They grew exponentially over the years in order to recover precious metals from the vast number of discarded objects left as a legacy by Capitalism and mass-production. The consequences of this mode of production resulted in an environmental and social crisis that lasted for years, but at some point, from its ashes something was born. A local, community-managed circular economy was put in place to exploit the potentialities of e-waste to get the resources that are no longer possible to get from the underground. Due to the scarcity of materials, electricity was no longer guaranteed 24 hours per day. Thus, people had to find new solutions, collectively. Someone looked back in history and re-introduced old, alchemic techniques to obtain energy from food waste and metals. Energy becomes something to be manufactured, to be crafted. Something that *people sense and live with, something they must care for. Below the ground, canteens are now used to store clusters of batteries connected with each other that power the energetic needs of each building when electricity is out. Citizens take turns in taking care of the clusters and replace the metals when they get exhausted. They go to the nearest metal collection point, which in most cases is located within a few miles for each neighbourhood.*

In this world, homes change configurations, and the home spaces are now used in unconventional ways. People move towards a do-it-yourself approach and try to be self-sufficient: it starts with the production of energy with the cluster of batteries, and it goes to the use of fogponics and hydroponics techniques to grow food. Every week, citizens gather in common spaces in the neighborhood to share insights, new techniques, and knowledge on how to recycle, repair and reuse objects, how to extract materials from waste, and how to make their own bio-based materials. Societies change at large as well, becoming more and more decentralized meshes and moving "back" into smaller communities.

The stories envisioned the described scenario where materials are scarce and urban mining is a common procedure. In some of the stories, participants imagined bottom-up processes where citizens would share knowledge on how to repair, re-use and build low-tech devices from waste. This aspect highlights the rising relevance that initiatives such the above-mentioned "The Restart Project" or "The Low-Tech Lab" could have in the next future within the field of repair and re-use of goods. An interesting point is that most of the narratives were not representing a dystopian world or a largely technological world, which is common talking about speculative design (Mitrović et all., 2021); on the contrary, the participants represented a world where collectivism and a renewed connection with natural resources are main paradigms.

As for the last point of the focus group, iii) insights on the feasibility of the method, the participants were able to write interesting opportunities of deployment but not as able in highlighting possible weaknesses or threats. It is possible that there was not enough knowledge and evidence to base this type of judgement on, both from the participants and from the authors. Thus, this point is a matter that needs to be further tested and explored.

The exhibition space as engagement

The final prototyping action unfolded over an exhibition, which happened between 20th-28th of May 2020 at Konstfack University. That was a key moment where public audience could engage with the author and raise questions or start a discussion over the project. The space was painted black, with a wooden wall built to project a film edited by the authors. The film aimed to inform the public of the context of the research: the main character was a human figure holding an open laptop on one hand, with a rock on the other hand and playing with the two materialities, so similar but so different at the same time. Moreover, all the metals required to make an Apple iPhone work are listed one by one (Merchant, 2017). At the centre of the room there was a black podium with the batteries and other materials researched over the prototyping phases. Moving from left to right, the materials on the table showed a process from raw materials, to electronics, then to the melted rocks of the first prototypes, ending to the ceramic batteries attempting to light a LED bulb or potentially slowly charge a smartphone (fig. 9). The closed cycle is symbolic in that case but aims to start discussions on the concrete strategies that could be developed and adopted from individuals, companies and policy makers for the necessity to “close the loop” within the electronic sector, and not only.

The exhibitions could play a significant role within experiential knowledge; not only in entertaining the public but also in educating the public to relevant issues and asking for their opinions or critiques (Barendregt & Vaage, 2021). Exhibitions are the fictional set where the audience discusses the speculative works, helping to imagine new future trajectories (Chen & Fu, 2021). Based on these assumptions, the exhibition space was intended as an open and accessible space to engage with the public on the topics of energy consumption and sustainability. The objects and material samples were purposely placed on a table accessible both for adults and children. The public was allowed to touch the materials and turn on the batteries. Giving the audience the freedom to interact with the space was useful because it helped reduce the barrier between the public and the artists/designers. Many interesting insights came especially from conversations with children, who were amazed to see a dark space filled with film, sound, and unusual objects on the table. While looking at the materials, few people engaged in a discussion on a possible future of material scarcity, where the ability of building DIY technologies and bio-based materials will be a public knowledge to share among citizens. It is interesting how four people that had never met each other before were discussing and designing a speculative scenario based on the experience of the exhibition and the prototypes.

Figure 9: Panoramic view of the exhibition space. Credits: Jesper Malsten

Moving on: conclusion and further actions

Experimenting with materials and organising a workshop allowed the authors to answer the research questions posed at the beginning of the research activity: how prototyping through material crafting can elicit and trigger a particular message and how to deliver that message to an audience and generate awareness on the topic of e-waste and consumption.

The participants were all design students; thus, they were already familiar with participatory and hands-on activities. In particular, the experimentation made direct observations on the material behaviours and on the intuitive interactions between participants and materials and confirmed how making can be a tool to think and reflect (M.A. Fariello, 2005). While observing the workshops authors noticed how collective manipulation of matter can arouse feelings of oneness with nature and between each participant. Tackling hopeful discussions on behavioural change and, ultimately, through material actions, could create awareness of problems but spark positive improvements to every one's behaviour and mobilise them to make behavioural changes regarding climate issues and sustainability.

Regarding this issue, the authors realize that small shift in a limited number of persons can trigger a significant change towards sustainability at the community level. Even a simple workshop could activate medium and long-term behavioural change; the performed activities were proven to be valuable in triggering both a new mindset as a designer and a more aware and responsible both individual and collective behaviour.

Indeed, few of the participants stated how they got curious to apply the method to other objects as well, and one participant mentioned how the recovered precious metals such as gold and silver could be used for an artisanal jewellery production. These testimonies how such activities can be remembered from the participants, stimulate virtuous practices and perhaps even new projects, such as the student who mentioned to make jewels from e-waste; in the shared experimentation, participants collaborated, learned from each other, and developed new knowledge and skills.

Building up from these premises, the role that these practice-led activities could have in design practice, while engaging with material development, innovation, and energy (engineers, scientists, technologists) is promising for creating a so-called *community of practice*, where individuals can learn from one another, share best practices, and stay up to date on the latest developments in their field. (Hoadley, C. 2012)

Crafting materials and prototyping within structured protocols through design practitioners and citizens engagement can be expanded beyond the connotation of testing in the product design realm (testing if a prototype works, which materials are best to exploit etc.) towards educational training in imagining possible futures or worlding through sensorial connection with the materials, or making (Wargsgeo & Alvarado, 2019). The approach used for the case study here described proved to be effective but needs to be replicated and improved (in terms of protocols and numbers of participants) for future research by also exploring potentialities of edutainment in exhibitions and a democratic community engagement.

In this regard the authors are already planning to execute another experimentation regarding sustainability by using digital lamps and exploring forms and material qualities of the strip led used in most of nowadays lamps. The workshop would engage students at Master Level in Design and Engineering (Politecnico di Milano) and it would reflect on the potential role of design in the creation of longer subject/object relationships to extend the product's life and defy the product's obsolescence (Cooper, 2010). Authors are proposing a collective activity based on the thinking-through-making approach where students would explore and test material qualities to embed in the design of their prototypes, with the aim of fostering a sense of care and forging speculative narratives with the object and materials in question, that blend the real with the yet-to-happen and the fictional (Helgason & Smyth, 2020). The activity will involve the scenario creation as well; authors are reasoning on implementing the co-created scenario through a backcasting framework, thus building a roadmap to the future envisioned and the necessary phases to get there. The results of the workshop in form of dynamic scenario, would be potentially shown in an exhibition where the public can access and give feedback on the experimentation, thus helping the students to move forward in their process and reflect on their own role as designers within the sustainability discourse.

Acknowledgement

The project started as MFA (Master of Fine Arts) thesis in Design at Konstfack University of Arts, Crafts and Design, supervised by professor Katja Pettersson, Jenny Althoff and Martin Avila. Subsequently it evolved in deeper research within the Design Department at Politecnico di Milano.

References

Acosta, A. (2017). Post-extractivism: from discourse to practice—reflections for action. In *Alternative pathways to sustainable development: Lessons from Latin America* (pp. 77-101). Brill Nijhoff.

Atzmon, L., & Boradkar, P. (Eds.). (2017). *Encountering things: Design and theories of things*. Bloomsbury Publishing.

Auger, J. (2013). Speculative design: crafting the speculation. *Digital Creativity*, *24*(1), 11-35.

Barbero, S., & Cozzo, B. (2009). *Ecodesign*. Ullmann.

Barendregt, L., & Vaage, N. S. (2021). Speculative design as thought experiment. *She Ji: The Journal of Design, Economics, and Innovation*, *7*(3), 374-402.

Black, A., & Burisch, N. (Eds.). (2020). *The New Politics of the Handmade: Craft, Art and Design*. Bloomsbury Publishing.

Blythe, M. (2014, April). Research through design fiction: narrative in real and imaginary abstracts. In *Proceedings of the SIGCHI conference on human factors in computing systems* (pp. 703-712).

Bennett, J. (2010). *Vibrant matter: A political ecology of things*. Duke University Press.

Broms, L., Wangel, J., & Andersson, C. (2017). Sensing energy: Forming stories through speculative design artefacts. *Energy Research & Social Science*, *31*, 194-204.

Broms, L. (2014). *Storyforming: Experiments in creating discursive engagements between people, things and environments* (Doctoral dissertation, KTH Royal Institute of Technology).

Coalition, E. W. (2019). A new circular vision for electronics: Time for a global reboot. World Economic Forum.

Cooper, T. (Ed.). (2010). *Longer lasting products: Alternatives to the throwaway society*. Gower Publishing, Ltd..

Dunne, A., & Raby, F. (2013). *Speculative everything: design, fiction, and social dreaming*. MIT press.

Fariello, M. A., & Owen, P. (Eds.). (2005). *Objects and Meaning: New Perspectives on Art and Craft*. Scarecrow Press.

Formafantasma (2017-2020). Ore Streams. Retrieved from http://www.orestreams.com/

Helgason, I., & Smyth, M. (2020, July). Ethnographic fictions: research for speculative design. In *Companion Publication of the 2020 ACM Designing Interactive Systems Conference* (pp. 203-207).

Hoadley, C. (2012). What is a community of practice and how can we support it?. In *Theoretical foundations of learning environments* (pp. 286-299). Routledge.

Johnson, B. D. (2011). Science fiction prototyping: Designing the future with science fiction. *Synthesis Lectures on Computer Science*, *3*(1), 1-190.

Jørgensen, N. J., Madsen, K. D., & Læssøe, J. (2018). Waste in education: the potential of materiality and practice. *Environmental Education Research*, *24*(6), 807-817.

Kappes, H. B., & Oettingen, G. (2011). Positive fantasies about idealized futures sap energy. *Journal of Experimental Social Psychology*, *47*(4), 719-729.

Kerridge, T. (2015). *Designing Debate: The entanglement of speculative design and upstream engagement* (Doctoral dissertation, Goldsmiths, University of London).

Kymäläinen, T. (2015). *Science fiction prototypes as design outcome of research*. Aalto University.

Kotler, P. (2010). The prosumer movement. In *Prosumer revisited* (pp. 51-60). VS Verlag für Sozialwissenschaften.

Latour, B. (1992). Where are the missing masses? The sociology of a few mundane artifacts. *Shaping technology/building society: Studies in sociotechnical change*, *1*, 225-258.

Lawson, L. (2021). The Anthropology of Precious Minerals. *The Journal of Gemmology*, *37*(5), 545-546.

Lionello, C. (2019). Broken Nature: Design takes on human survival, XXII° International Exhibition, La Triennale di Milano,«Op. cit.», n. 165, May 2019, pp. 77-80 (catalogue's review). *OP. CIT.*, *165*, 77-80.

Mader, A., & Dertien, E. (2016). Tinkering as method in academic teaching. In *DS 83: Proceedings of the 18th International Conference on Engineering and Product Design Education (E&PDE16), Design Education: Collaboration and Cross-Disciplinarity, Aalborg, Denmark, 8th-9th September 2016* (pp. 240-245).

Merchant, B. (2017). *The one device: The secret history of the iPhone*. Little, Brown.

Mitrović, I., Auger, J., Hanna, J., & Helgason, I. (2021). *Beyond speculative design: past–present–future*. University of Split.

Panu, P. (2020). Anxiety and the ecological crisis: An analysis of eco-anxiety and climate anxiety. *Sustainability*, *12*(19), 7836.

Peters, J. D. (2015). The marvelous clouds. In *The Marvelous Clouds*. University of Chicago Press.

Rognoli, V., & Parisi, S. (2021). Material Tinkering and Creativity. In *Materials Designers. Boosting talent towards circular economies* (pp. 20-25). Elisava.

Rozendaal, M. C., Heidingsfelder, M. L., & Kupper, F. (2016, August). Exploring embodied speculation in participatory design and innovation. In *Proceedings of the 14th Participatory Design Conference: Short Papers, Interactive Exhibitions, Workshops-Volume 2* (pp. 100-102).

Santulli, C., & Rognoli, V. (2020). Material tinkering for design education on waste upcycling. *Design And Technology Education: An International Journal, 25*(2), 50-73. Retrieved from https://ariadnestaging.lboro.ac.uk/DATE/article/view/2713

Tharp, B. M., & Tharp, S. M. (2022). *Discursive design: critical, speculative, and alternative things*. MIT press.

Von Handorf, D. R., & Crotty, D. E. (2002). The Baghdad Battery: Myth or reality?. *Plating and surface finishing*, *89*(5), 84-87.

Walker, C. J. (2010). Experiencing flow: Is doing it together better than doing it alone?. *The Journal of Positive Psychology*, *5*(1), 3-11.

Wargo, J. M., & Alvarado, J. (2020). Making as worlding: young children composing change through speculative design. *Literacy*, *54*(2), 13-21.

Williams, K. A. (2011). "Old Time Mem'ry": Contemporary Urban Craftivism and the Politics of Doing-It-Yourself in Postindustrial America. *Utopian Studies*, *22*(2), 303-320.

Young, L., & Davies, K. (2013). A Distributed Ground: The Unknown Fields Division. *Architectural Design*, *83*(4), 38-45.
Zeng, X., Mathews, J. A., & Li, J. (2018). Urban mining of e-waste is becoming more cost-effective than virgin mining. *Environmental science & technology*, *52*(8), 4835-4841.

Zimmerman, J., Stolterman, E. & Forlizzi, J. 2010, "An analysis and critique of research through design: Towards a formalization of a research approach", *Proceedings of the 8th ACM Conference on Designing Interactive Systems*, ACM, pp. 310-319.

Giorgia Burzio

Giorgia Burzio is an interdisciplinary designer and researcher. She is currently a Research Fellow at the Department of Design of Politecnico di Milano mainly collaborating to the project of D\Tank, the Think Tank of the Department.
In her work, she translates complex environmental dynamics and invisible phenomena into tangible objects, material experimentations, and experiences.
She initially studied industrial product design at Politecnico di Torino, with a focus on systemic and material design, attentive to the social and environmental dimensions of the product. She subsequently moved to Stockholm, at Konstfack University of Arts, Crafts and Design, where she obtained a Master of Fine Arts (MFA) in design through a thesis project on the flow of materials used in electronic devices, proposing a thinking-through-making approach to co-create future scenarios on the use of such resources. She was a recipient of a merit scholarship offered by the Konstfack Rector in June 2021. She was artist-in-residence at Fabrica Research Centre (Treviso) and a contractual collaborator at POLI.design.

Venere Ferraro

Venere Ferraro, PhD in Design, is an Associate Professor at the Department of Design at Politecnico di Milano.

She has been Visiting Researcher at University of New South Wales of Sydney (2006) and at Media Lab of Massachusetts Institute of Technology (2009) where she run research on Wearable Systems and electronic textiles with the lens on design-driven and user-oriented approaches.
She participated in several International and National research both as coordinator (DATEMATS”-KA2-2018, POD: Plurisensorial-SAF€RA 2014 joint call) and as principal investigator (Destex- Strategic PA and In Transit- HEurope).
The research interests lie in the domain of *interaction design*, more in detail: the role of *wearable technologies, emerging materials, and big data* in designing experiential systems for digital care, with particular attention to *speculative tools and methods* for changing user behaviour.
There are two key elements that strategically guide her activity: the interdisciplinary and international dimension of the area of design research and practice and the integration between the research and the teaching activity. Specifically, the integration between the research and the teaching activity is developed through research projects mainly conducted for SMEs where the focus is to stress the design role as lever to achieve and improve innovation.

Think with your hands: Exploring the Future via Prototyping

Hazal Gumus Ciftci, Arizona State University
Konnor Plymire, Arizona State University

Abstract

Wearables are constantly becoming more present in our daily lives. Paired with our smartphones and smart homes, wearable devices such as smartwatches and earpieces are aimed to support our endeavors; though at times they invade our personal lives to the point where our communication with the outside world is mostly through these products. Therefore, for our graduate industrial design studio course at Arizona State University, we have set out to design wearable technology products that take all life forms' well-being into account for the future. We benefited from trend research, design fiction, speculation, wizard of Oz techniques, and concept-knowledge mapping. Prototyping was one of the key methods used to discover how to lead the design propositions for this student project. Master of Industrial Design (MID) students at Arizona State University during Fall 2022 were asked to build– but more importantly, think– with their hands and turn their tacit knowledge and imagination into wearables that will help and care for the end-users. This paper will illustrate the design process used in the studio and how different levels of prototyping helped the MID students' "think with their hands" and how it allowed the abstract notion of designing for the future to turn into a concrete understanding of creating life-centered designs.

Prototyping, Design Futures, Wearable Technology, Speculative Design

It is important for industrial designers to physically prototype because of their constant relationship with three-dimensional space. Bringing a design into the tangible world allows the designer to touch their creation and view it in the reality it is meant to be a part of. There's a reason car companies still make full-scale clay models--even with advancements in CAD and rendering technology. Viewing the contours, ridges, and valleys of your creation in real space allows you to see potential problems that you may not have caught otherwise. It also gives you the opportunity to check your work from the perspective of the end or target user. The need to design for the 'human element' is another important use of prototyping, especially the rough, early-stage models. These models are usually made to check scale, form, and feel; the shape of a handle, or other touch points can be gripped, used, and felt. Sometimes you can only ensure a product fit in a hand or on the body of a user if you make it yourself and check.

This 2nd-year MID studio project was developed to be an experiment lab with multiple stages of prototyping. The prototypes completed in these stages ranged from low-fidelity mock-ups to approaching higher-fidelity prototypes. For this project, student designers were expected to design wearable objects as a brand extension for sports, fashion, and medical brands. These wearable objects are being designed to tackle the social/ individual well-being issues of the society in near future (5 years).

The objectives of this project were:

1. Developing an understanding of brand identity,
2. Understanding the needs for brand extension and market,
3. Visualizing a future product in context,
4. Creating a robust scenario that tackles social/ individual well-being issues in near future,
5. Prototyping a future-oriented product by using a variety of diverse methods.

The eight-week project started in the second half of the semester, culminating with a final presentation at the end of the academic term. The final presentation included a panel of guest reviewers and took place in the form of speed dates with three-minute presentations and feedback through post-its. This provided a short-format presentation with real-time feedback from reviewers for each individual student. As a result, students were able to show their prototypes in a limited timeframe to build a futuristic view as tangible and grounded products for the reviewers.

Designing Wearables in the 21st Century

Wearable technology products are considered as both ‘a device and a garment’ (Dunne, 2004, p.2) and are ‘different forms of body-mounted technology, including wearable computers, smart clothing, and functional clothing’ (ibid.).

> *Wearables, also referred to as body-borne computers, are small electronic or sensor devices that are worn on the physical body—either on the bare skin or on top of clothing… Today, wearable devices span the gamut from smart rings, bracelets, and necklaces to smart glasses and watches, to smart gloves, socks, and t-shirts. Moreover, wearables don’t stop at humans. (Levin in Follett, 2014, p.65)*

Pailes-Friedman cites eMarketer saying “in 2015, 29.5 million US adults 18 and over, used wearable devices (including fitness trackers and smartwatches), an increase of 57.7 percent over that of the 2014 wearable devices market” (2018). A more current report on wearables claims that ‘the global wearable technology market size is expected to grow at a compound annual growth rate of 14.6% from 2023 to 2030’ (grandviewresearch,2022).

Wearable technology products approach a range of categories from ‘outfit-centric design’ to aspiring to ‘jewelry design’ (Jarusriboonchai and Häkkilä, 2019). The authors then suggest that ‘wearables are argued to be more than just beautiful and functional’ (ibid., 2019). Wearable technology can be a bridge between function and fashion, allowing personal expression through customization while providing the intended utility of the device. Devices can be designed and added to in such a way that allows for inclusivity across a plethora of groups and demographics (Mizoki cited in Jarusriboonchai and Häkkilä, 2019).

Pailes-Friedman (2018) says that it seems a likely and logical progression that wearable technologies would evolve from objects we wear on our bodies, to our bodies themselves. That the same expression and utility offered by wearables today would be integrated into enhancements to the human body. Advances in prosthetics, cybernetics, and nanotechnology are likely to allow for a development of this nature.

Speculating Life-Centered Design Solutions

As the studio's main question was orbiting how we, as designers, might address the societal issues surrounding wearable technologies, and how we can create more humane design solutions geared towards an inclusive society, one of the main methods of the studio was speculative design. Our first goal was to open conversations in the studio by speculating on 'probable, possible, and preferable futures' (Candy, 2010).

To address this type of question, the field of future studies has developed numerous methods from forecast to foresight to prospective scenarios. Some of those future-oriented methods like forecasting rely on hard evidence to make projections while other methods like prospective scenarios tend to rely on observable trends to suggest a breadth of potential outcomes and possibilities. Other methods like speculative design– which can be considered as a subset of the prospective scenario approach–use artists' and designers' creative mindset to delve into potentialities without concern for the likelihood of seeing these scenarios come to fruition. Mitrovic says that speculation enables designers to develop and envision 'alternative products, systems, and worlds' (2015). As such, speculative design must be understood as a useful endeavor 'to think about the future and to critique current practice' (Auger, 2013). Dunne and Raby (2013) also point out that speculative design benefits from 'imagination' to develop new ways for solving' wicked problems. Therefore, engaging in the development of prospective scenarios through speculative design presents opportunities to open up and initiate conversations about diverse areas of the future. Moreover, speculative design implies 'how things could be' while considering the potential disadvantages that these designed objects would bring to society (SpeculativeEdu, 2018). It's about creating matrices of variables and considering those variables in a certain context, time, and usage; traveling as many avenues as possible to collect the necessary data.

> *The natural sciences are concerned with how things are… Design, on the other hand, is concerned with how things ought to be. (Simon, 1988, p.69)*

Pondering these issues, as a design studio we set out to tackle societal developments for the next five years with a brand extension that would support, care for, or take into consideration of life-centered design solutions. The students were encouraged to imagine a future in which their product would exist, and the benefits it would bring to the users of that reality.

The Design Process in the Studio

Given that the studio is very much related to humanizing emerging technologies and adapting existing or signaling changes in a considerate way, we adopted a life-centered design approach. Katie McCurdy, who is a design researcher working in healthcare, says the cyclical process of HCD consists of learn/ distill/ make/ test and refine stages and breaks them down into activities that could run in every different step (2017). Learning stage which is often referred to as "empathizing" consists of interviews, observations, shadowing people, and running workshops. Distilling or defining consists of persona creation, diagramming, coding, and journey mapping. Ideation is the step in which designers generate solutions to their problem definitions; brainstorming, prototyping, sketching, and storyboarding are some methods to use in this step. Then testing these ideas and refining them are the last stages of a human-centered approach. Adapting Katie McCurdy's cyclical HCD process into being life-centered required more iterations than just cycles as she suggests (2017).

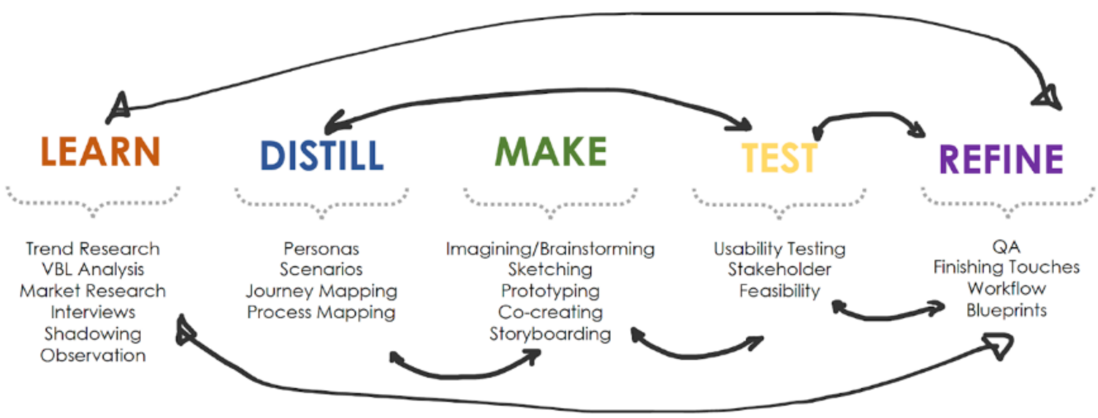


Figure 1. Human-Centered Design Process to Life-Centered Design Process adapted from McCurdy, 2017

The students began with trend research on well-being and used the knowledge they collected to decide which brand(s) might go into the wearable sector in the next five years. The selection included SpaceX, Dyson, Adidas, and Nintendo and DeWalt.

Additionally, for the "learn" step of the design process, trend research revealed the signaled approaches in scientific and technological developments. Assistive technology in well-being, performance-supporting wearables, emerging technologies' use for new products, and alternative material use were among the trends which the student groups identified.

After the trend research commenced, the individual work began, and the students dove into distilling and making sessions right away. With ideation exercises such as brainstorming, sketching, scenario planning, concept-knowledge mapping, and journey mapping a plethora of diverse approaches started to flourish in the studio. In the latter stages, the students presented their two different concepts to their peers and instructors, each student selected one concept and carried it into the making stage.

For testing, student designers used their early prototypes and scenarios. They identified and interviewed potential future users and used the resulting data to refine their prototypes. Just as every stage, prototyping and refinement took turns and finally twenty future wearable prototypes were put on display at the end of the term to a selection of faculty members. Students did three- minute presentations of their projects and got feedback to refine their projects for later use. Feedback from the students after showed that the format of design presentation "Speed Dates" was effective and was even reported as a lower-stress alternative to traditional presentation/critique styles.

Prototyping in the Studio

The aim of prototyping in different situations is varied. In engineering it might be to check tolerances, clearance, or provide a proof-of-concept working model; in design, it's sometimes for understanding the users' needs and sometimes for understanding the needs of production. Hallgrimsson says ‘Prototyping is a key problem-solving activity in product design’ (2012, p.7). In our case, our goal for prototyping was to comprehend how people would interact with a future-oriented design in terms of ergonomics and psychology. After all, ‘prototypes are now described not only as the first verification of the product-to-be but also as a valuable instrument for the fuzzy-front end of design’ (Camere &Bordegoni, 2016, p.155). The expansion of prototyping from the production of a realized product to a tool for research, testing and gathering valuable information about the experiences of the user is especially prevalent when prototyping in lower fidelity.

Low-fidelity prototyping is as much a thinking process and conceptualization exercise as it is the creation of a physical model. Its’ purpose is to provide another angle of perception, answer a question, or verify an idea or decision. It is most commonly utilized when a design is still coming to fruition and isn’t yet fully realized by the designer; basic questions of scale, shape, and usability are at the forefront at this time (Sefelin et.al., 2003).

We started using pipe cleaners, aluminum foil, blue foam, and EVA foam to get started with low-fidelity models (Fig. 2-3). This stage allowed us to adjust the scale, fit the products better to our objects, and change features quickly. The students took to the materials well as they were approachable and easy to shape. Although those were the materials that were recommended, the students were free to explore with anything they preferred or wanted to try.

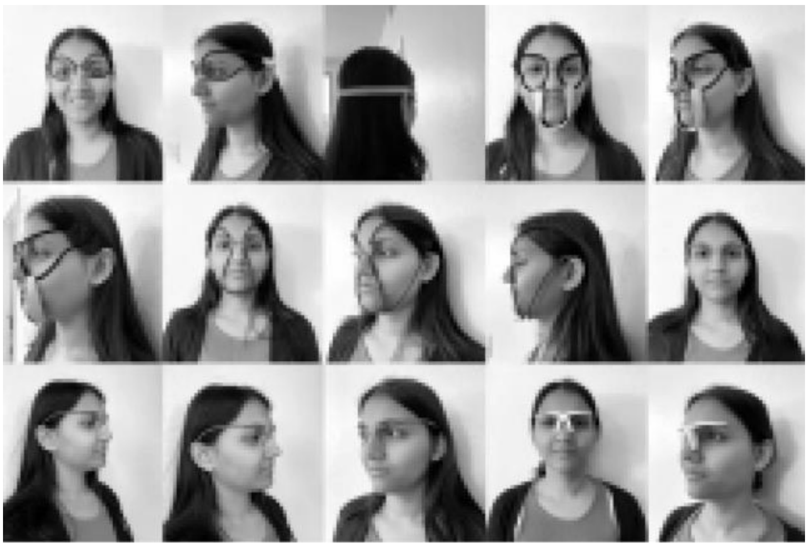


Figure 2. A student’s early explorations with tape and pipe cleaners (Image credit: Juhi Gajjar)

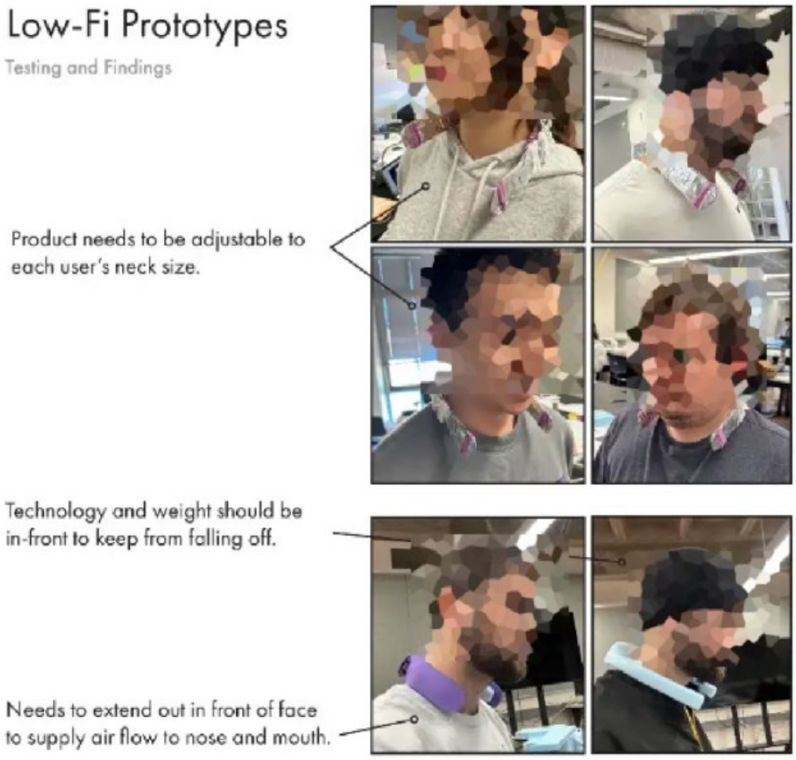


Figure 3. A student's early explorations with EVA foam, blue foam and Aluminum foil (Image credit: Brady Reichardt)

Finalizing the Concepts

A set of–at minimum– three iterations along with quick prototypes was to be completed before the products were taken to a 3D printing facility at the university. Final presentations included these appearance prototypes along with 3D CAD renders. Deploying these types of deliverables in tandem allowed the final product to be viewed both electronically in its' future-facing reality, as well as physically in reality of the designer and viewers alike.

Musical Therapy Earpiece

In this project, the designer used a thermoplastic elastomer to mimic the flexible nature of the earpiece to fit different users. This universal design is projected to collect physical data to interpret the mood of the users and then suggest music accordingly**.**

Figure 4. Evolution of Prototypes for Musical Therapy Earpiece (Image credit: Kyudo Lee)

A variety of 3D printed prototypes (Fig.4) allowed the designer to decide on the final material and make room for creating a universal fit by deciding on a malleable and adjustable fitting for the earpiece. The prototypes also allowed the designer to make small adjustments to the model to tweak and alter the adjustment and fit “range” of the product.

Figure 5. Final Render for the Musical Therapy Earpiece (Image credit: Kyudo Lee)

Sign Language Translating Pendant

Another project looked into the unique needs of deaf creative professionals. The designer created a pendant (Fig. 6-7) fitted with a camera that captures the sign language being communicated with a motion sensor and translates it to different language options. As sign language has many versions much like spoken languages, this would be an invaluable tool for any deaf professional or traveler.

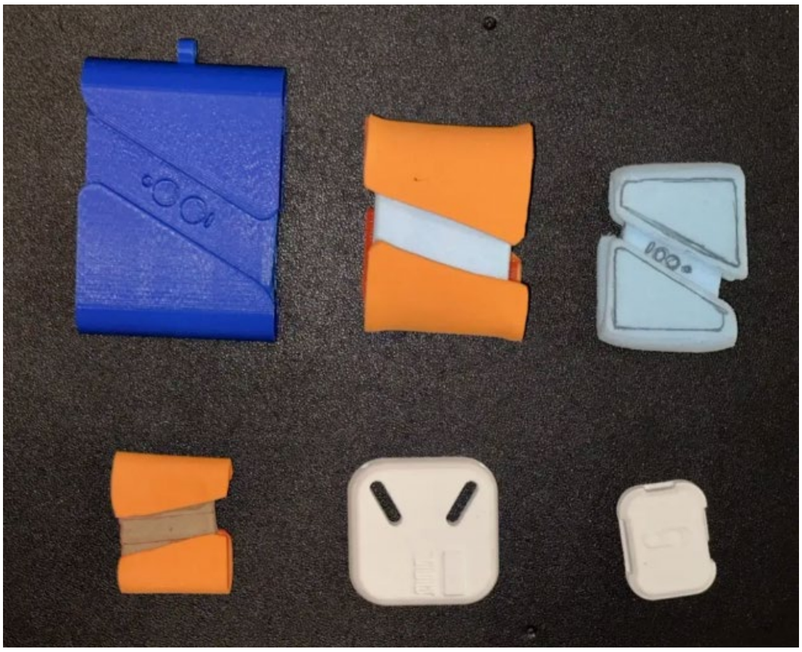


Figure 6. Evolution of Prototypes for Sign Language Translating Pendant (Image credit: Rishi Jaju)

Figure 7. Final Render for Sign Language Translating Pendant (Image credit: Rishi Jaju)

Why did we prototype?

Our decision for early prototyping lies in Camere & Bordegoni's words: 'Prototypes ultimately solve the need of learning about a design, asking questions and answering them. Sometimes, the purpose is to imagine a future-to-be' (2016, p.158). Talking about their robotics project with teens, Bjorling et.al. (2018), explain that in the beginning stages of the project, they began making and using rough prototypes to conduct interactive and reactionary studies. They then add:

> *The main theme that emerged from the qualitative, observational interaction study data was strong engagement with the low-fidelity prototype. We saw almost all participants with engaged and expressive faces while interacting with the prototype (ibid., p.70).*

While talking about the importance of configuring the user in wearable technology design Dunne (2004) says ‘beyond remaining aware of the entire scope of possible influencing variables, the designer must also remain aware of his/her influence on the identity of the target user: physically, cognitively, and socially’. The significance of the designer making decisions in such a complex project required us to start the prototyping as early as possible. It is only by collecting information for us–experientially and from the perspective of the target user–that we may begin to account for the seemingly infinite variables associated with all facets of the state of the user before, during, and after interacting with the product.

Camere and Bordegoni say “the purpose of involving users in a co-creative session at the early stages of conceptual design may suggest the use of low cost prototyping techniques, as paper and cardboard” (2016, p.157). As mentioned above the starting materials for prototyping were pipe cleaners, EVA foam, and aluminum foil which were developed in a collaborative attempt with the potential users. From that stage, students elaborated several iterations in different stages of the design process. Using prototyping, student designers were able to justify their ideation and storyline along with their decisions about form, function, and usability. An expert in designing wearable technology and e-textiles, Pailes-Friedman (2018, p.2) states:

> *We need to be able to rapidly prototype garments that have both function and beauty. These new wearable sensing products need to function and be comfortable, breathable, washable, fit well and have style. To get a product into the pipeline, designers need to [be] able to communicate their ideas, not just how a product works but how the end-user interacts with it and how it will look, feel, and fit when it is finished.*

Considering that our task was creating wearable technology products for the future, we agreed with Pailes-Friedman and started prototyping at an early stage with most projects and did several iterations. Student designers reported that they have created between three and ten prototypes. There was one account in which the designer started making prototypes as early as the learning stage and the majority of the designers initiated their prototyping in the third stage which is the making stage.

What did we learn from prototyping?

At the end of the project, design students received a survey asking about their experience with prototyping during the 8 week-long studio project. All design students agreed that prototyping helped them in a plethora of different ways. The majority of designers said that the benefits of being able to quickly decide on size and fitting were prominent. A good number of the participants pondered about how prototyping helped with functionality and determining if that functionality would work for the intended user. Some mentioned that the ‘making’ phase changed their perception of material selection, project stages, and even form decisions.

Quick Decisions on dimensions and form

Most participants of the survey mentioned how quick prototyping was beneficial in deciding the size, form, and even the functionality of early design ideas. The first question posed for the survey was “how did prototyping help you during the design process and explain why”. One of the designers stated:

> *Yes, prototyping was a very crucial part [of] my project as it helped me visualize my concept in physical form, I was able to identify shortcomings in my initial design, and with the help of user testing I was able to figure out the form and usability of my concept and was much satisfied with the final outcome.*

It was one thing on paper and the design started to materialize and went beyond when the prototyping started. Another designer pondered:

> *I was able to explore appropriate dimensions for a wristwatch while still keeping the proportions a bit playful, and making the band allowed me to explore CMF options.*

A key takeaway from early quick prototyping was how the designers were able to iterate on their ideas and how prototyping encouraged them to realize errors more effectively. If [as the designer/creator] you experience these errors firsthand, it is easier to momentarily jump into the shoes of a potential end-user and see things from their perspective. We found that by establishing a tactile link to the object, the designer is much more empathetic and connected to the ultimate benefits of their end-user.

Material Choices

The studio started the prototyping sessions right after the first round of sketching/ ideation exercises. Due to the wide variety of forms in both the wearable products themselves and the body parts they would need to conform to, materials and methods were varied and adjusted for each individual project. Suggested materials were pipe cleaners and EVA foam sheets in this round; some designers used aluminum foil as a support material. Not only were these materials extremely malleable and easy to work with, but they also carry with them an almost playful perception of approachability that encourages designers to love their mistakes and to not be afraid of trying, testing, and experimenting with their designs. Among the other materials utilized was cardboard, chosen for its role as a rigid, planer material. It’s cheap, structural, light, and very forgiving for the type of quick-conceptualization prototyping done in this stage.

In the latter stages, the majority chose to advance their designs using rapid prototyping opportunities such as 3D printing. Printing allowed some students to rapidly grow, test, and fine-tune models; making adjustments in a fluid and dynamic way to ensure fit and comfort. When reaching the stages for the final display model it was a simple process to clean, smooth, paint and finish the decided-upon “final print”.

Gathering Feedback

Another takeaway from the prototyping was how it offered the designers a vehicle for gathering feedback from their potential users. Despite the rough and low-resolution nature of prototypes used in participatory design, end-users can provide valuable feedback by imagining the potential of the product when instructed correctly, while in other cases, stakeholders of the product development process can also be the audience for prototyping activities (Camere &Bordegoni, 2016). Their models became props in their discussions, classmates became size gauges and sounding boards, and they were able to gather data from a subject's experience with their object and not just an opinion of another. This gave the designers a crucial chance to fix errors, take their ideas to the next step, and create more meaningful interventions in wearable technology products. One of the designers added:

> *It [prototyping] was very helpful as it allowed me to iterate quickly on different design concepts. I could easily figure out the curves and flow of form by looking at the prototype. I used the prototypes to test it on the users and got their feedback.*

As the first author ran this project as a 'clean studio' four times before; gathering feedback from potential users and reviewers alike has been more effective and reliable in terms of finding a common ground. These prototypes from early on in the design process supported designers' endeavors of creating a future vision and allowed them to tell more engaging stories of their creations.

Conclusion

With this project, student designers were asked to develop a future vision for wearable technology products and prototyping allowed them to ground their ideas and share them with the reviewers as credible and feasible concepts. Prototyping is one of the key skills of industrial designers and it aids in decision-making, quick iterations, and the delivery of ideas more dramatically. This studio course having a focus on emerging technologies and life-centered design proved that prototyping is also beneficial to create more credible and robust solutions for the future. Designers were able to fail early and adapt quickly. Additionally, they were able to design the whole future-oriented experience that these products might be offering. Products ranged from allowing smoother communication for deaf creatives to people searching for a better state of mind. All the concepts became more meaningful with the support of prototyping and all the student designers (n=20) agreed that prototyping assisted tremendously in reaching their goals.

Acknowledgments: We would like to thank 2nd year MID students at Arizona State University and Collin Smith for their continuous curiosity and playfulness throughout the project and the prototyping sessions.

References

Auger, J. (2013). Speculative design: crafting the speculation, Digital Creativity, DOI:10.1080/14626268.2013.767276

Björling, E. A., Rose, E., & Ren, R. (2018). Teen-robot interaction: A pilot study of engagement with a low-fidelity prototype. In Companion of the 2018 ACM/IEEE international conference on human-robot interaction (pp. 69-70).

Camere, S., & Bordegoni, M. (2016). A lens on future products: An expanded notion of prototyping practice. In DS 84: Proceedings of the DESIGN 2016 14th international design conference (pp. 155-164).

Candy, S. (2010). The Futures of Everyday Life: Politics and The Design of Experiential Scenarios. The University of Hawaii at Manoa.

Dunne, A. & Raby, F. (2013). Speculative Everything: Design, Fiction, and Social Dreaming. The MIT Press. Boston.

Dunne, L. (2004). The Design of Wearable Technology: Addressing the Human-Device Interface Through Functional Apparel Design. MA Thesis. Cornell University. August 2004.

Follett, J. (2014). Designing for Emerging Technologies: UX for Genomics, Robotics, and the Internet of Things. United States: O'Reilly Media.

Grand View Research (2022). Retrieved from: https://www.grandviewresearch.com/industry-analysis/wearable-technology-market#:~:text=The%20global%20wearable%20technology%20market,consumers%20is%20driving%20industry%20growth [Accessed on 12th December 2022].

Hallgrimsson, B. (2012). Prototyping and Modelmaking for Product Design. United Kingdom: Laurence King Publishing.

Jarusriboonchai, P., & Häkkilä, J. (2019). Customisable wearables: exploring the design space of wearable technology. In Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia (pp. 1-9).

McCurdy, K., (2017). Human-Centered Design Process Diagram. Retrieved from https://katiemccurdy.medium.com/human-centered-design-process-diagram-ac8f5eeb411b [Accessed on 15th September 2022]

Mitrovic, I. (2015). Introduction to Speculative Design Practice – Eutropia, a Case Study. [Online] Available at: http://interakcije.net/en/2015/05/10/introduction-to-speculative-design-practice-eutropia-a-case-study-2/ [Accessed 19 January 2023].

Pailes-Friedman, R. (2018). Electronics and Fabrics: The Development of Garment-Based Wearables. Advanced Materials Technologies, 3(10), 1700307.

Sefelin, R., Tscheligi, M., Giller, V. (2003). Paper prototyping - what is it good for? a comparison of paper-and computer-based low-fidelity prototyping. In CHI '03 Extended Abstracts on Human Factors in Computing Systems (CHI EA '03). Association for Computing Machinery, New York, NY, USA, 778–779. https://doi.org/10.1145/765891.765986

Simon, H. A. (1988). The science of design: Creating the artificial. Design Issues, 67-82.

SpeculativeEdu. (2018). SpeculativeEdu. [Online] Available at: http://speculativeedu.eu/. [Accessed 20 January 2023].

Hazal Gumus Ciftci

Hazal Gumus Ciftci is an assistant professor of industrial design at Arizona State University. Her research interests are design for sustainability, social innovation, local production, crafts, and meaning making through cultural rituals.

Gumus Ciftci holds a doctorate in design from Lancaster University. She received her bachelor's degree from Istanbul Technical University (industrial design) and a master's degree from Politecnico di Milano (product/service/system design).

Konnor Plymire

Konnor Plymire is a faculty associate at Arizona State University. He teaches Digital Process- Advanced Parametric CAD Modeling and prototyping. Konnor studied sculpture at University of California Santa Barbara and industrial design at Arizona State University.

Prototyping Dialogues

Louise Ravnløkke, Design School Kolding, Denmark
Thomas Binder, Aalborg University, Denmark

Abstract

For designers and design researchers, the ecological crisis and the quest for sustainability do not only mean a re-orientation in what design provides in terms of products, services, and systems. It also demands a change in how design is done, acknowledging that sustainable design and use have to co-evolve through speculative dialogues addressing a radical re-configuration of both the crafts of making and the crafts of use. This paper is an attempt to revisit one of the key tenants of contemporary design practice, the prototype, to find a language of prototyping that can sensitize us to what evolves when engaging with future sustainable practices through such speculative dialogues.

In this paper, we dive into three co-explorative design engagements of a research project on sustainable knitwear design to further explore what we call prototyping dialogues. Through these accounts of prototyping dialogues, we argue that prototypes are outcomes of the dialogues rather than distinct proposals from the designer to be iteratively presented and evaluated. Furthermore, we suggest that the prototype, as an outcome, comes about through a dialectic between different modes of engagement which we term the ‘experiential’ and the ‘experimental’, having both material, performative, and speculative manifestations in the collaborative encounters.

Prototypes; Design Engagements; Prototyping; Sustainability; Collaborative Encounters

The prototype has been around for a long time. Far beyond the professional fields of design, the prototype has been adopted as a core vehicle for iterative processes where proposals for new products, services, and systems become manifest through design engagements in real-life settings. Prototyping approaches have turned traditional development processes on their head designing ‘from through the interface’ (Bødker, 1991/2021) and exploring head-on the experiences of living with prototypical proposals. The prototype is seen as a concrete suggestion coming with a question of what this suggestion entails for the user (and designer). This has led to a way of talking about prototyping as a procedure of presenting and testing a possible change where what is presented is subsequently re-designed and represented according to the outcomes of the test (Koskinen & Frens, 2017; Westerlund & Wetter-Edman 2017). While this certainly captures the experimental and iterative aspects of a prototyping methodology, it says less about what a prototype can be or what the dialogue involves.

Within classical design fields, e.g., industrial design or interaction design, typologies of prototypes are well established, reflecting well-known ways to communicate and evaluate design proposals (Evans & Pei, 2010). These typologies continue to be useful, and as prototyping methodologies have become more widespread, the specificity of what is prototyped (Lim, Stolterman & Tenenberg, 2008) and the accuracy of evaluation have increased significantly (Wensveen & Matthews, 2014).

Many have emphasized how prototyping enables a rich dialogue between designers and users (see, e.g., Sanders & Stappers, 2008). In this dialogue the envisioning of new products, services, or systems are typically pivotal, taking relatively stable practices of use as the ground from which the implications of what is proposed are collaboratively interrogated. We want, however, to explore what happens to prototyping when design is moving into the uncharted terrain of radical re-configurations of design and use as they unfold in the transitions toward sustainable everyday practices of, e.g., fashion and clothing. Fletcher and Tham have argued that the continuing increase in over-consumption within the fields of fashion and textile calls for a fundamental re-orientation of both the practices of design and use (Fletcher & Tham, 2019). Suggesting a grounding for design and use in what they call an ‘Earth logic’ they claim the need for fashion to embrace simultaneously a fundamental shift in the crafts of making and crafts of use responsibly addressing the ecological crisis. Following this move prototyping becomes less of a test of ‘solutions’ and more of a co-exploration of ‘preferable futures’ (see also Dunne & Raby, 2013 and Malpass, 2016). In line with Fletcher and Tham, Twigger Holroyd (2021) has proposed inquiries into ‘fashion fictions’ as a productive step to envision fashion differently. She invites the proposal of fictional worlds of caring design and use to be explored through the speculative staging of prototypical practices. Similarly, Andersson and colleagues engage with prototyping futures of urban living ‘beyond efficiency’ to open up different imaginaries of sustainable living (Andersson et al., 2019).

Even in more mundane engagements with the re-direction of making and use like the ones we will elaborate on in this paper the emphasis on co-exploration and co-speculation in our view is essential to bring about possible change. Prototyping as an iterative and experimental process exploring the experiential qualities of imagined practices of designers and users offers a productive frame for these engagements as a series of probings, rehearsals, and tentative enactments of proposals (Halse et al., 2010). To get hold of what is prototyped and how proposals come about we find however, that we must turn to a broad definition of the prototype (from Merriam-Webster Dictionary) as “an original model on which something is patterned (similar to an archetype).” And further, we suggest that the prototype, as an original model, is not what the designer brings to the user, but instead, what comes out of the prototyping dialogues. Seeing the prototype as an outcome of dialogues can help us to hold on to what this ‘original model’ is within the narratives of the livable worlds it invokes.

To think of the prototype as an outcome of dialogues rather than as a starting point crafted by the designer may seem counterintuitive. Nevertheless, we find it worthwhile exploring what this slight shift in definition from the prototype as a means for dialogue to the prototype as an outcome of dialogues may add to how we understand and take part in prototyping dialogues.

We have three things we hope to accomplish. First, we want to find out if this definition shift can help us to stay within the design engagements as we become knowledgeable of the possible worlds they reveal. All too often, we have found that prototyping is reduced to means through which we produce data, gain insight, or test concepts, distancing us from the knowledgeable thinking and doing in the dialogues.

Secondly, we want to pick up on Redström’s (2017) claim that the design inquiry makes theory by probing into how prototyping dialogues produce knowledge of both a particular here-and-now and of a horizon of potentialities. By drawing on this idea of situated theorizing/knowing, we seek to overcome the conventional hierarchy of instantiations/specifics as special cases of the generic, conceptual, or theoretical, inherited from conventional schemes of systems thinking and still present in discussions of theory building in design research (see e.g., Zimmerman & Forlizzi, 2008).

Lastly, we hope to add to a more nuanced understanding of the different modes of engagement through which prototyping dialogues unfold. While we acknowledge the straightforwardness of the notion of testing prototypes, we think that we will gain from a richer vocabulary addressing the experiential and experimental qualities of the material, performative, and speculative manifestations and enactments of the prototype as an outcome of dialogues.

We will explore this by revisiting the prototyping dialogues of a particular doctoral project on sustainable knitwear design conducted by Ravnløkke (2019), with the tentative definitions we have introduced above. At the heart of this doctoral project is the assumption that knitwear design can become more sustainable if technological options for customized products can be combined with processes of design and use, where the designer and user move together in dialogues all the way from the research of user preferences and needs to the trial use of novel designs. In all these dialogues, Ravnløkke implicitly or explicitly stated a 'what if' question by bringing samples in the form of knitted swatches or finished knitwear that opened the dialogues towards worlds of possible use. While Ravnløkke, in the project, called these concrete material props, knitted prototypes, one could as well (as Ravnløkke has also done, and what we together develop further below) see the overall staging of the dialogue as a prototype of a trend forecast, a business model, or a practice of future use. As we revisit Ravnløkke's work, we will look for prototypes emerging in the dialogues that can be understood as 'a general model on which something is [or can be] patterned'. This does not mean that we will question or criticize the relevance of what Ravnløkke, in her project termed, knitted prototypes. On the contrary, we hope to understand better what these props 'do' in the dialogues and to more fully grasp the characteristics and potentials of the prototyping design practice (also inspired by Binder, 2016), suggested through this work (Ravnløkke, 2019; 2021).

Methodologically, Ravnløkke's doctoral project is grounded in practice-based design research constructing scenarios and artifacts to carry out engagements with participants. In this way, the research is undertaken as a programmatic exploration where various engagements co-evolve in a dialectic with the program (Brandt et al., 2011; Redström, 2017).

In the following, we will present three of these engagements exemplifying prototyping dialogues. Each example will be used to unfold and provide nuances to the discussion. In the end, we will conclude the exploration by returning to the above-mentioned queries.

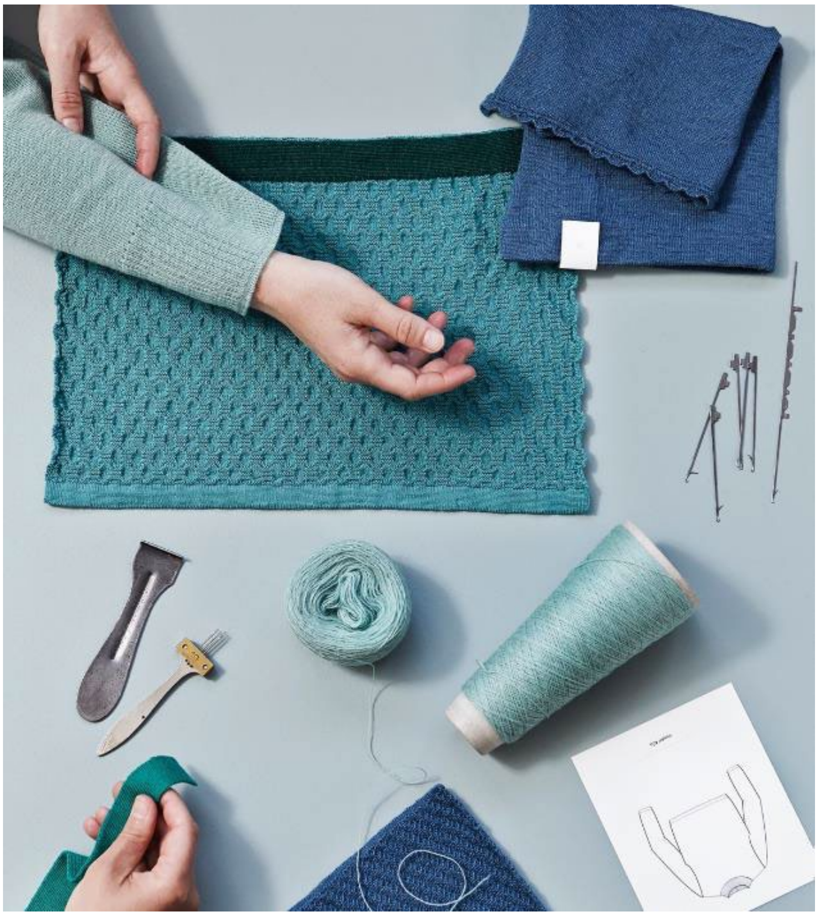


Figure 1: Example of prototyping dialogues (Author 1, xx).

Material dialogues

In the first example of prototyping dialogues, we dive into conversations about garment use. The design engagement invited users to elicit insights into use of knitwear and to envision experiences of use of jumpers. By addressing the use phase, the designer can consciously work to increase satisfaction with clothing and prolong garments' lifetime (Niinimäki, 2011). From a sustainability perspective, it is advantageous to postpone the disposal stage and to increase the intensity of use (Laitala et al., 2015). Therefore, the conversations in the engagement sought to study how fit, material qualities, and aesthetic preferences influence how often knitwear is used.

The engagement was set up as a series of conversations with three female participants. Knitted artifacts were brought to the conversations by the designer and acted as conversation pieces alongside the participants' knitwear wardrobe. In this way, the engagement was drawing upon both wardrobe methods (Fletcher & Klepp, 2017) and the Repertory Grid interview technique (Bang, 2013) to create the framework for a dialogue that could embrace and exemplify everyday use and sensory experience.

The conversations took place in the participants' own homes. The artifacts comprised a selection of six knitted textile samples and six jumpers. Additionally, the participants' knitted wardrobe was brought into the conversation to evoke both personal and social aspects of the use of knitwear (Klepp & Bjerck, 2014). In that way, the garments from the participants' wardrobes also ‘took part’ in the dialogue. The artifacts guided the articulation and dialogue and created a common basis for an in-depth conversation about the participants' experiences with the use of knitwear.

Figure 2: An artifact in form of a jumper and the application of it in conversation with a participant.

The different knitted textiles were brought along to form the basis for the conversation about the tactile and visual experience of structures, patterns, and colors. The purpose of the jumpers was to direct the dialogue toward shape, fit, and details. To further obtain insights into the participant’s experiences of quality and durability, some of the jumpers showed signs of wear or tear, such as peeling, discoloration, holes/run stitches, and shrinkage after washing. Including the participants’ knitwear wardrobe had the purpose of diving even more into use situations, use relations and use frequency.

In the dialogue, the knitted textiles and jumpers, as well as the participant's wardrobe, acted as catalysts for evolving narratives. With direct reference to the samples, participants could tell stories eliciting personal preferences and elaborating on possible use practices. This is reflected in a participant’s description of her preferred style of garments in one part of the conversation and again later in the conversation, where she elaborates this narrative based on garments from her wardrobe:

“I have always thought that cardigans are very practical, but then I use something like this instead – an open shirt. The function of a cardigan is very good, but I have never found one that I like. /…/ Sometimes I have tried cardigans, /…/ but the cut – where it stops – is not very becoming. It stops a really ugly place that doesn’t do any good for that many.”

In continuation of this statement, she says that she uses open shirts the same way as a cardigan to take off and on to regulate body heat. Her open shirts are longer so they cover the hip's widest place. Reviewing her knitwear wardrobe also shows that she does not own a single cardigan and that her favorite type of knitwear are short jumpers which do not highlight the hip area:

"I actually use this a lot when it's winter. It is not that long, so I can wear it with high-waisted trousers.”

"I think it has a funny shape. It has slightly trumpet-like sleeves and goes out a little at the bottom, but it is still short. So, I also use it quite a lot.”

The narrative brings an understanding of how particular styles and shapes make the participants feel comfortable and good-looking in relation to imagined use situations and practices. To have the knitwear present and accessible is key to bringing about such narratives in which knitwear's physical, emotional, and social dimensions are intertwined. They originate in explorations of the experiential qualities of the artifacts. Still, they also hold an experimental probing into what knitwear design might be that goes well beyond what the prototypes immediately entail.

Generating a dialogue about use of knitwear

Coming back to our initial suggestion that a prototype is better conceived of as an outcome than a starting point, we can ask what kind of prototypes emerge in the conversations on garments in use, which we have briefly presented here.

First, it is worth noting that the staging of the conversation, as a dialogue between designer and user, made manifest through the design artifacts, already frames the dialogue very differently from conventional user research. The artifacts are guideposts in a landscape of possible design envisioned by the designer and become, in this way, an implicit 'what if' question in which the user can mirror her own preferences and aspirations. The user can answer this 'what if' question by pulling knitwear from her wardrobe, but also by telling speculative stories of use relating to what the designer has brought 'to the table'. As the dialogue evolves, narrative threads are spun that qualify the appreciation (or depreciation) of the artifacts (brought or found) in the light of this imagined landscape of possible design. The materiality of the artifacts invites for an open-ended exploration of tactility, color, pattern, fit, etc., that have an immediate experiential side to them for the user and the designer. For the user this engagement is guided by such questions as: 'How could this thing be on my body' while the question for the designer could be 'How could this be [an appreciated] part of my design?

Here the appreciation does not have to be stated in isolation from the artifact. It can rather be seen as a sort of annotation to it that can be addressed and elaborated upon in a dialogue in which the artifact itself takes part.

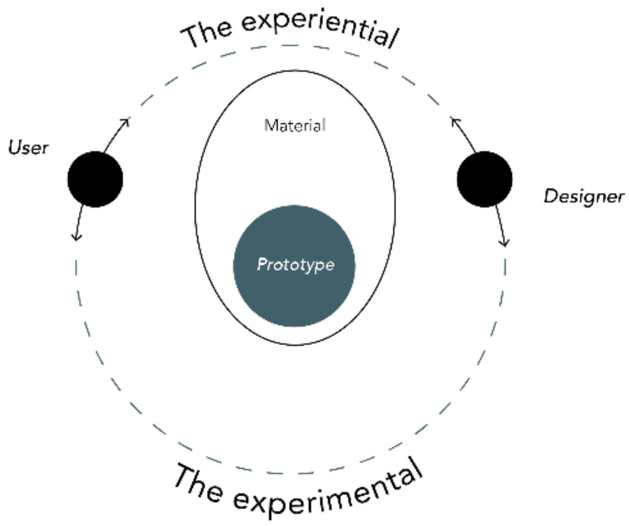


Figure 3: Manifesting the dialogue through the material.

The narratives evolving in the dialogue do, however, also point toward other future artifacts. In the design landscape, collaboratively envisioned, the narrative probes into the virtual by asking: Could this [prop] be such a thing [as the general model of the knitwear we envision]? This aspect of the dialogue is what we call the experimental. The shared 'what if' is hypothetical, also in the sense that neither designer nor the user knows what the landscape will bring. When the participant elaborates on the cardigan, as somewhat practical, yet stopping at 'a rather ugly place', we are not only getting into why she does not like cardigans but also as a kind of shadow image starting to see with her what beautiful and practical knitwear 'could be'. These and other narrative threads evolve in correspondence with what Ravnløkke, as a designer, brings to the dialogue. The short jumper, both literally brought into the dialogue as a conversation piece and presenting itself as a (proto-) type to be explored, braids the participants' practice of, e.g., taking on the jumper accommodating body heat with the imagined appreciation of the shape of the trumpet-like sleeves. The dialectic between the experiential exploration of 'how could this be my jumper?' and the experimental probing into 'how could this be a jumper' revolves around the conversation pieces. As the dialogue unfolds, a jumper design manifests itself as a prototype. This prototype is formed as an outcome of the co-evolving bricolage of what we can think of as annotations to the conversation pieces and relations between them established in the narratives.

The design engagement brought a shared understanding of what could be considered of value to the prototype with respect to emerging categories of visual expression, style of the jumper, proportions and fit, and material tactility. Further, it became the springboard for envisioning a customized jumper, where design choices for the user are made accessible through material artifacts that also function as aesthetic and functional guideposts in the design landscape envisioned through the dialogues.

Finally, this prototype also came to hold prototypical qualities for how designer and user could be designing together, mutually exploring the design landscape within a hypothetical business scenario of customized design, production, and use. This became the starting point for a new round of engagements (described below).

Prototypes rehearsed and performed

In the second example of prototyping dialogues, we look further into the performativity of prototypes. This design engagement consists of a series of workshops in which 46 users were invited to select their favorite jumper based on a business scenario for customized knitwear design. When making design choices for their preferred jumper, the participants engaged with various knitted samples, color swatches, and working drawings. They could make design choices about the style of the jumper, the material quality and stitch pattern, and color. Furthermore, participants had the option to select details of the sleeves and the color detail of the hemlines. These relatively few options provide 97,200 variations of jumpers, which is an extremely large collection giving a wide range of options to personalize from – aesthetically and fit-wise. Compared to acquiring a jumper from a traditional knitwear collection, where the choices are far more limited, this artifact of customized knitwear design required something else from the participants. The set-up of the engagement allowed participants to act out and explore what this 'something else' comprises.

Prototyping user involvement in knitwear design

The design engagement showed that the participants had the skills, courage, and fancy to make these design choices. It also revealed how these choices emanated from an intense engagement with the material samples provided as guides in the design landscape.

The participants treated the samples as experiential anchoring points for narratives of what their choices would look like and how these would fit in with the rest of their wardrobes.

Figure 4: Material samples and their application in the business scenario workshop with participants.

The samples were explored by touch and held against the body to consider choices. They were examined by stretching to assess elasticity and dimensional stability and visually judged when the colors were compared by placing them next to each other.

The exploration of the experiential qualities of the samples evolved within a workshop where the participants were also invited to act out a role as customers in a shop-like setting where their engagement with the choices extended well beyond a conventional shop counter interaction. The participants had the time to accustom themselves to the different choices and to talk to each other while they tried out the jumper designs and probingly examined appearance and performance. More than half of the participants chose to design the jumper based on ideas of usability and frequent use. They considered how their design choices would visually suit their personal style and preferred colors by imagining how the jumper could be used with their other clothes. Furthermore, the participants showed an awareness of what they themselves thought would suit them compared to their body shape. The participants included experiences from previous use situations and took advantage of the design parameters to make personal choices. Some participants preferred simple and neutral expressions, while others wanted to disrupt a simple or neutral expression with contrasting details.

Several jumper designs were manifested from these rehearsed and performed engagements with knitwear design. In combination with the individual narrations of use, the representations of jumpers became prototypes of an open design process acting out an altered relationship between the design and the user.

As the participants rehearsed and performed how to be a customer/designer in this business scenario of customized knitwear design, they enacted considerations and choices leading to individual designs which stand out from mainstream trends. Even though the participants expressed having chosen what they themselves saw as ‘safe choices’, these would not appear as safe choices for others. By entering the hypothetical 'what if' of a shop/workshop space where they could interact with the designer and with fellow customers to accomplish an individual design, they could experimentally challenge what is a basic jumper or a classic expression. This made them move towards designs they felt confident in choosing because they thought the jumper would suit them well and could be worn on many occasions.

These modes of rehearsing, performing, and speculating within the prototypical frame of a different designer-user relationship were further explored through a third design engagement entering the more intimate relations of everyday use.

Prototyping speculation

In the third example of prototyping dialogues, the design engagement stems from a curiosity towards what happens in use when the user is involved in the design process. What does it mean to be a part of the design process? How does it affect using the jumper? And how does it affect use relations? Three participants' choices of jumpers were produced to act as design probes (Mattelmäki, 2006). The jumpers were given to the participants with an encouragement to take pictures of themselves when wearing them. Over a period of an entire year, the use of these jumpers was photo-documented by the participants and texted to Ravnløkke. Sometimes a brief description of the use of the jumper and on the occasion was attached to the photo.

A jumper is used together with other clothes, thereby creating an outfit of personal expression. Following the use of the jumpers, allowed Ravnløkke to dive deeper into how they would be included in the participant's wardrobe and how the participants would combine the personalized jumper with other garments. Throughout the one-year period, two interviews were conducted with each participant. These interviews were primarily based on the photos and text messages sent from the participants. While the self-documentation showed fragments of the use phase, the conversations became an opportunity to explore further use situations and ways of using the jumper.

Figure 5: Employment of the materiality of self-documented use situations and the personalized jumper.

The interviews and self-documentation showed how the participants used the jumper as an integral part of their existing wardrobe. The participants found personal ways to use the jumper, along with selected garments that they thought *went well* with it. Likewise, they added their own 'design parameters' through use and styling.

What made this design engagement different from, e.g., a study of garment use, with participants with no prior involvement with prototyping a close user-designer dialogue, was that the engagement prompted a speculative attitude for both the users and the designer. The participants knew very well what had led to the specific design, and they also knew that the jumper had come out of a process that was, in itself, a proposal for a different relationship both between user and design and between design and use. In the responses to this situation, there were many examples of how the participants not only rehearsed and performed novel dressing practices with their personalized jumpers. They also expanded on the hypothetical 'what if' by entering into new cycles of design in use. One of the participants often used a brooch to close her cardigan when she thought it was too cold, to have it open. At the same time, she experienced how it, to her, gave a distinctive character that makes it more personal – as she could shape the cardigan around the body and highlight her waist by putting in the brooch. In this way, she continues to contribute to the design by taking ownership of the garments' expression in the use phase.

Figure 6: Personalized jumpers and one of the jumpers in use.

With such bodily speculations, the participants deliberately sought to open further their capacities for engaging with design and personal expressions. A good example of this sense of empowerment is the strong connection between the participant´s personal preferences, individual aesthetic experience with the jumper, and the use frequency of it. While neutral and classic visual expressions by designers are often associated with the design being used in many contexts, the participant's involvement with the design process opened another dynamic of use where frequent and active use relates more to colors and stylistic expressions matching the participant's preferences. In this way, the co-explorative engagements with the personalized jumpers manifested as a prototype of a new consumer role challenging assumptions that neutral and classic visual expressions provide the only route toward more frequent and long-lasting garment use (Niinimäki, 2014).

The speculative attitude also turns out to have a direct impact on the participants' wardrobe metabolism. For some of the participants, their individual styles changed as they experimented with everyday use of the personalized jumpers. One of the participants was very determined about her color preferences being grey, marine blue, and black – which the inventory study of her wardrobe also established in the first design engagement. During the third design engagement, this changed as she stated that her "new color [was] green" like the one she had selected for her personalized jumper in the second design engagement. She showed what new items she had acquired in this color as a part of experiencing her newfound style expression. Just as employing the jumper prototype assisted the participants in speculating about using garments, the example of the insight of color preferences initiates speculation of how user involvement in the design process potentially contributes to empowerment and confidence about personal expressions: A speculation that also illustrates a potential for designers to focus to a greater extent on clothing that allows the user to take ownership of the expression during the design process and also through the everyday practices of use.

The prototype reconsidered: from a means to an end

What have we then gained from revisiting the terms of prototype and prototyping through Ravnløkke's project? We think that we have come to see how much of what is learned from this project is deeply rooted in the particularity of possible worlds that comes about in the prototyping dialogues. The design artifacts brought into the dialogues afforded both an experiential exploration and an experimental probing into what worlds of living with design and use of customized jumpers could be, which in itself, offers a novel methodological approach to sustainable design and use.

In retelling the project, we have sought to get closer to this knowledge produced in the dialogues. Rather than emphasizing data analysis and generalizable insights on, e.g., user preferences or design potentials, we have instead attempted to get at the particular narrative figures of fit, shape, tactility, etc., that emerge in the correspondence between the designer/researcher and user evolving through the experiential and experimental encounters with the artifacts.

Table 1: Examples of modes of engagement in prototyping dialogues.

Design engagement	**Material** *Design artifact*	**Performative** *Scenario of engagement*	**Speculative** *Possible world*
1. Use of knitwear	Knitted samples and the user's knitwear wardrobe	Wardrobe interview	What might be future design/use practices based on user needs and preferences?
2. User involvement in knitwear design	The artifact of customized knitwear design	Shop-like setting and design choices	What if the user is involved in the design process?
3. Use of personalized jumpers	The personalized jumpers	Everyday outfit selection and wearing	How might the user-design relationship be in an open design process?

The table gives an overview of the modes of engagement in the three prototyping dialogues we have revisited in this text. While the overview clarifies the examples of the different modes, it also provides examples of the experiential and experimental qualities that are present across material, performative, and speculative manifestations of the prototyping dialogues.

To come closer to what emerges in these dialogues and how experiential and experimental perspectives relate, we will return to the broad dictionary definition of the prototype as "an original model on which something is patterned," we have throughout this paper sought to show how this original model becomes the result of an engagement between the designer/researcher and the user. Prototypes are present in each of the design engagements; they are not the means or design tactics that make the narrative figures emanate from the dialogues. On the contrary, the prototypes *are* these figures coming about in the dialectic between the experiential and the experimental aspects of the dialogues.

The design artifacts occasion the experiential here-and-now that makes the narrative figures and representations accessible. Thus, the prototype is not a knitted sample, a drawing of shapes, or a full mock-up of a jumper, yet these artifacts in the dialogues come to embody speculative tales of imagined or real experiences that bring the design and use of knitwear together in novel configurations. In such tales, the physicality of samples, drawings, and exemplars certainly participate, but the particular coming together comes to life in the dialogue.

In connection with this, we suggest that prototyping may productively be re-considered as the doing and thinking which emerge in the course of a dialogue.

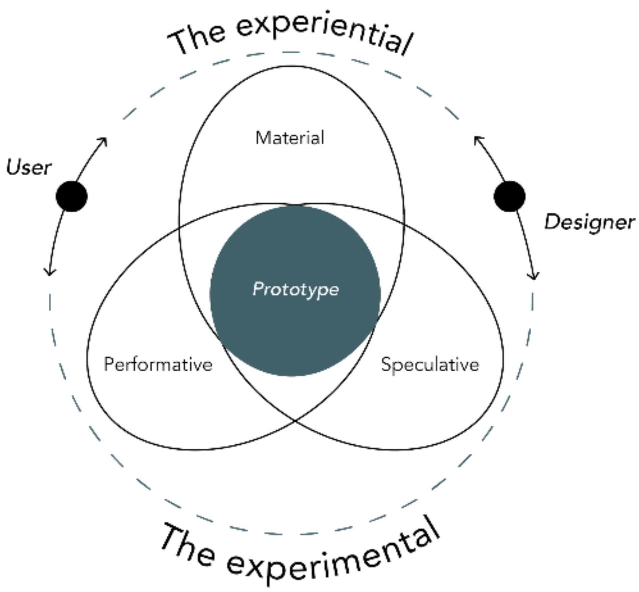


Figure 7: Prototyping dialogues.

We will further argue that prototyping occurs in the dialogues when the engagement of both 'designer' and 'user' encompasses the experimental and the experiential while opening up landscapes of possible design, connecting the here-and-now with a horizon of potentialities.

What is envisioned and enacted in the dialogues are figures of design and use entangled with the material, performative, and speculative manifestations of the interactions. The material and yet performative and speculative vibrancy of the encounters between designers and users are what caters for the emergence of a prototype as an original model (archetype) on which something can be patterned.

Being open to this more nuanced and transformative understanding of what makes a prototype may assist designers/researchers to venture into the uncharted terrain of future sustainable practices of design and designing with a wider palette of evocative design artifacts and a broader repertoire for staging and learning from the collaborative encounters. In line with Redström's argument that design theory is "unstable, fluid, and dynamic in character" (2017: 2), it may be useful to think of the prototype as such a theory of possible futures invoked through a dialectic of experiential and experimental modes of engagement with what such (yet to come) futures may entail.

References

Andersson, C., Wangel, J., Broms, L., Molander, D., Runberger, J., & Ehrnberger, K. (2019). Beyond Efficiency.

Bang, A. L. (2013). The Repertory Grid as a Tool for Dialog about Emotional Value of Textiles. Journal of Textile Design Research and Practice, Vol. 1, nr. no 1: pp. 9–26.

Binder, T. (2016). The things we do: encountering the possible, book chapter in Smith, R. C., Vangkilde, K. T., Otto, T., Halse, J., Kjaersgaard, M. G., & Binder, T. (Eds.). Design Anthropological Futures. Bloomsbury Publishing.

Brandt, E., Redström, J., Eriksen, M. A., & Binder, T. (2011). XLAB. The Danish Design School Press.

Bødker, S. (1991/2021). Through the interface: A human activity approach to user interface design. CRC Press.

Dunne, A., & Raby, F. (2013). Speculative everything: design, fiction, and social dreaming. MIT press.

Evans, M., & Pei, E. (2010). ID Cards. Loughborough University.

Fletcher, K., & Klepp, I. G. (2017). Opening up the Wardrobe: A Methods Book. Novus.

Fletcher, K., & Tham, M. (2019). Earth logic: Fashion action research plan. JJ Charitable Trust.

Halse, J., Brandt, E., Clark, B., & Binder, T. (2010). Rehearsing the future. The Danish Design School Press.

Klepp, I. G., & Bjerck, M. (2014). A methodological approach to the materiality of clothing: Wardrobe studies. International Journal of Social Research Methodology, 17(4), 373–386.

Koskinen, I. K., & Frens, J. (2017). Research Prototypes. Archives of Design Research, 30(3), pp. 5-15.

Laitala, K., Boks, C., & Klepp, I. G. (2015). Making Clothing Last: A Design Approach for Reducing the Environmental Impacts. International Journal of Design, 9(2), pp. 93–107.

Lim, Y. K., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Transactions on Computer-Human Interaction (TOCHI), 15(2), pp. 1-27.

Niinimäki, K. (2011). From Disposable to Sustainable: The complex interplay between design and consumption of textiles and clothing. Aalto University, School of Art and Design.

Niinimäki, K. (2014). Green Aesthetics in Clothing. Normative beauty in commodities. Artifact, Vol 3, Issue 3.

Malpass, M (2016) Critical Design Practice: Theoretical Perspectives and Methods of Engagement, The Design Journal, 19:3, pp. 473-489.

Merriam-Webster Dictionary. https://www.merriam-webster.com/dictionary/prototype [Accessed April 27, 2023]

Ravnløkke, L. (2019). Design af strikbluser til lang levetid: Strikkede prototyper som redskab for brugerdialog i designprocessen [Design of Knitted Jumpers for Longevity: Knitted Prototypes as a Tool for User Dialogue in the Design Process] [Dissertation series]. Design School Kolding.

Ravnløkke, L. (2021). Prototyping scales of knitwear design for sustainability. Conference Proceedings. NORDES Conference, 15-18 August 2021, Kolding, Denmark.

Redström, J. (2017). Making design theory. The MIT Press.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. CoDesign, 4(1), pp. 5–18.

Twigger Holroyd, A. (2021). Fashion Fictions: unmaking the mainstream fashion system. https://fashionfictions.org [accessed April 27, 2023]

Wensveen, S., & Matthews, B. (2014). Prototypes and prototyping in design research. In The routledge companion to design research. Routledge, pp. 262-276.

Westerlund, B., & Wetter-Edman, K. (2017). Dealing with wicked problems, in messy contexts, through prototyping. The Design Journal, 20(sup1), pp. S886-S899.

Zimmerman, J. & Forlizzi, J. (2008), 'The role of design artifacts in design theory construction'. Artifact, 2:1, pp. 41–45.

Louise Ravnløkke

An Assistant Professor, Ph.D., engaged in skills development within sustainable transition – skills which entail sensory aspects of both the designer and the user of textile products. Louise has a background in textile design practice which she employs in her research. Her experimental and practice-based Ph.D. research 'Design of Knitted Jumpers for Longevity: Knitted Prototypes as a Tool for User Dialogue in the Design Process' is a result of bringing together design practice and academia. The overall objective of the project is to generate knowledge that can contribute to sustainable change through an open design practice, with the intention to support the textile designer's role in this development. Today Louise is still occupied with this field applying her practical and aesthetic skills of being a designer in combination with a conceptual mindset. This is implemented in her work within research, development projects, and higher education, where she finds interest in exploring the role of the designer in a world in the transition of sustainable change.

Thomas Binder

A researcher and educator engaging open design collaborations and participatory design in the context of social innovation and sustainable transitions. His research includes contributions to methods and tools for experimental design research and open innovation processes with a particular emphasis on codesign and design

anthropology. He has been editing and authoring several books such as (Re-) searching the Digital Bauhaus' (Springer 2008), Rehearsing the Future (Danish Design School Press, 2010), Design Research through Practice (Morgan Kaufman, 2011), Design Things (MIT press, 2011) and Design Anthropological Futures (Bloomsbury, 2016). He has been chairing the Participatory Design Conference in 2002, the Nordic Design Research Conference in 2005 and the Design Anthropological Futures Conference in 2015.

Design Fiction Prototyping to tackle Societal Challenges and support Design for Sustainable Behaviours

Mila Stepanovic, Independent Designer and Researcher

Abstract

This paper introduces a research project investigating the role of design fiction prototypes in design research and practice to tackle the Grand Societal Challenges, sustainable user behaviours, and the role of technologies in supporting the process of building thriving futures. Dealing with the pervasive technological development and increased demand on societal challenges, there is a need to imply critical reflection and take equal action at all levels of transformation. The potential of design research and practice to tackle societal challenges and influence human behaviour is well established. Technological artefacts actively shape ones being in the world, actions, experiences, and habits. The current tools and methods used in the design research and practice concerned with designing technologies to tackle human behaviour frame the user as merely an executor of a specific behavioural programme without considering the broader context in which an individual exists. The author describes a new critical approach used to generate two design fiction prototypes, engaging experts from different fields of study (neurosciences, social psychology, design research, behavioural design, digital design, and design for sustainability). This paper shows how such an approach can be integrated into design research and practice to anticipate unintended behavioural outcomes and the ethical implications behind using technology to trigger sustainable behaviours. The critical approach aims to shift the attention from purely cognitive aspects of human behaviour to experiential ones to understand how people make sense of the world and explore new social and interaction rituals that may lead users to adopt and preserve sustainable behavioural patterns and practices. The design fiction prototypes delivered throughout this research were tested in focus groups. In conclusion, the author reports the results from focus groups and discusses the benefits and limitations of such an approach. Finally, this paper introduces possible future developments.

Sustainable Behaviours; Grand Societal Challenges; Technologies; Design Fiction Prototyping; Conscious Design

People and societies are engaged in complex systems and events in the contemporary world, such as political and economic debates, conflicts, environmental issues, and rapid scientific and technological development. (Grand and Wiedmer, 2010)

Haunted by the ideal of progress, societies often lack solutions for present problems. (Escobar, 2017) There is a need to imply critical reflection at all levels of transformation to deal with the complexity. (Berry, 1999)

Design research and practice play an important role in the transformation toward more sustainable futures by providing the methods and tools to support the understanding of complex systems and engage the broader public in collective reflection and action.

This paper introduces the research investigating the role of Design Fiction Prototyping as a tool to tackle Grand Societal Challenges (GSCs), sustainable user behaviours, and the role of technology in building thriving futures. The author introduces the critical approach exploiting Design Fiction principles to support design researchers and practitioners in dealing with the complexity and adopting critical thinking when designing with and for technologies to tackle sustainable behaviours. The critical approach emphasizes the experiential dimension of human behaviour. Understanding how people make sense in and toward the world is essential to design the social and interaction rituals that can support the users to become more aware of the environment.

Emerging Critical Design Practices (CDPs), such as Design Fiction, strive to generate social action through fictional projects to inspire real-world actions. (Dune and Raby, 2013)

Design Fiction is speculating about the future through prototyping and storytelling. It is “the capacity to imagine and make concrete not yet existing products and services.” (Ilstedt and Wangel, 2014) Design Fiction is a strategy for more explicitly attending to the feedback loop between fictional imagined futures and actual technology design. (Bleeker, 2010)

The author shows how design research can benefit from design fiction prototyping and engages experts from different fields of study to generate envisioning scenarios on the future of technological artefacts to support sustainable behaviour addressing some of the most emerging societal challenges. These scenarios informed the development of design fiction prototypes, which were tested with users in focus groups.

In the last part of this paper, the author introduces the results and discusses the critical approach exploiting the design fiction prototyping, its benefits and limitations.

Background

The foundations of this research lie in the intersection between the Design for Behavioural Change, Human-Computer Interaction (HCI), and Design Fiction.

The current methods and tools used in the design and research on technologies to modify human behaviour (i.e., changing an individual's behaviour regarding health and wellbeing, work, safety, environment, and others) usually frame the user as merely an executor of a specific behavioural program without taking in account the changes in an individual's life circumstances and the outer world (social context). (Rapp, Tirassa, and Tirabeni, 2019)

Recently, the scientific community recognised a need to rethink the current behavioural models, tools, and methods to shift the attention from purely cognitive and behavioural aspects to experiential interactions. Rapp et al. (2019) suggest that Phenomenology may offer a framework "for understanding how people make sense of existence in and toward the world" and "allows for the expression of people's perspectives about a given phenomenon, trying to understand it within their universe of sense." Such an approach could change how technologies are designed to tackle human behaviour and grasp a broader context of events and actors when it comes to an understanding the individual in the world.

Secondly, many ethical questions have been raised about technology's pervasive development and implementation. There is a demand for analysing the technologies and technological systems not as independent entities but as active participants in society. Technological artefacts are not neutral; they actively co-shape peoples' being in the world. (Verbeek, 2006) Finding approaches and methods to open the technology to a broader range of interests and concerns "could lead to its redesign for greater compatibility with the human and natural limits on technical action." (Feenberg, 2005)

The Human-Computer Interaction (HCI) field is increasing its interest in Design Fiction due to the pervasive development and integration of technologies and a need to question the ethical aspects and contextualisation of the technologies in the real world. Design Fiction prototypes typically "employ a culturally familiar form […] to depict, often in a mundane and matter-of-fact way, imagined future products, services, or scenarios in order to tell story around them, and by doing so, pose questions." (Bleeker et al., 2022)

Beyond imagining how the future looks and feels, some of the questions that design fiction prototypes may raise are: What are the potential implications of our choices? How might we change what we are doing to make the possible outcomes more desirable? (Bleeker et al., 2022)

An Introduction to Critical Approach exploiting Design Fiction principles

The critical approach introduced in this paper is an output of the three-year research (November 2018 - November 2021) on using design fiction principles to trigger critical thinking and deliver a more conscious design of technologies to address sustainable behaviours and Grand Societal Challenges.

The critical approach integrates the principles from Design Fiction to the already established methods used in design research and practice. These principles include building future scenarios and design fiction prototyping.

Figure 1 illustrates how the Critical approach can be integrated with the traditional design and research process and methods to explore the feedback loop between the future and present and deliver a more conscious design of technologies.

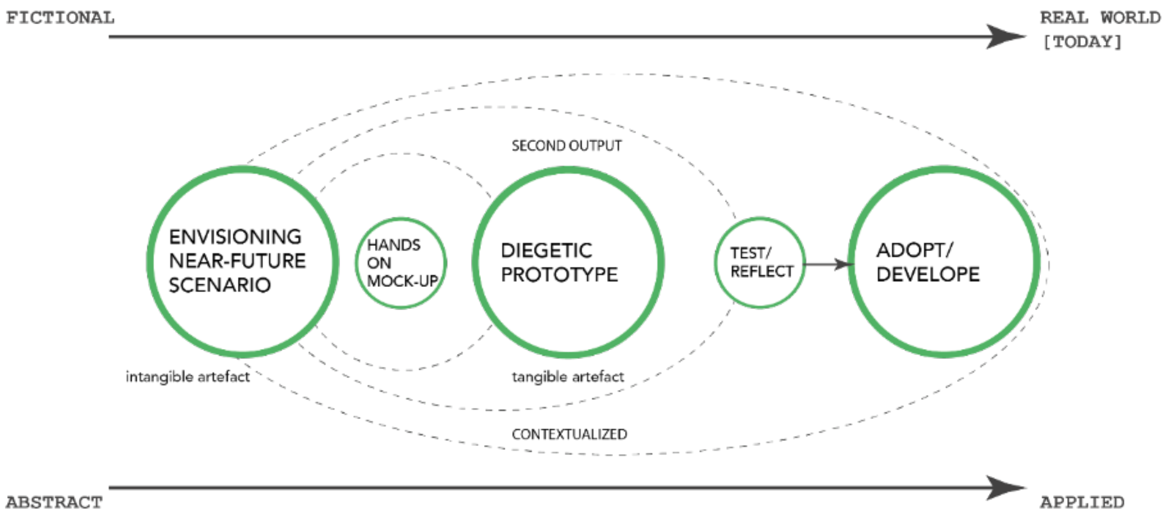


Figure 1: Critical approach to design technological artefacts to tackle sustainable behaviours illustrated by the author

To support the design researchers and practitioners with the practical tools and methods throughout the critical approach, the author generates the Protocol for designing consciously and the Envisioning Tool. The Protocol for designing consciously and Envisioning Tool represents guidelines, methods, and tools to generate envisioning scenarios and materialize them. The critical approach was developed for design researchers and practitioners operating within the sphere of product and service design.

The Protocol for designing consciously is divided into four stages (Figure 2). Each stage applies the theories, tools, and methods from different fields of study (design research, philosophy of technology, HCI, social sciences, neurosciences, psychology).

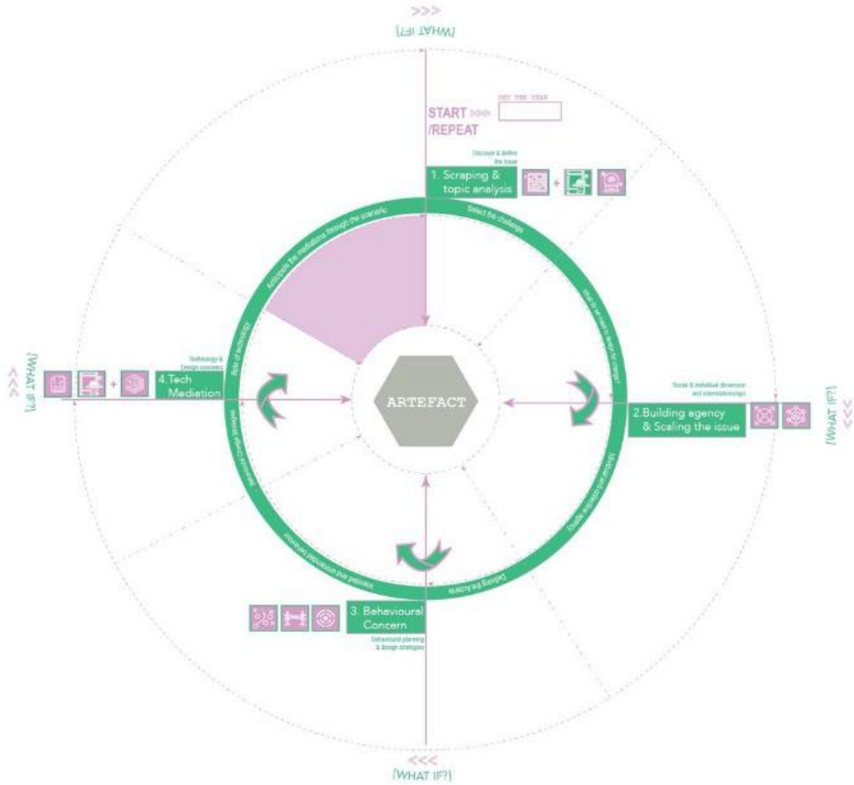


Figure 2: Protocol for designing consciously developed and designed by the author

Envisioning Tool is a library of cards categorised into Tech Inspiration Cards (TICs) and Societal Inspiration Cards (SICs) (Figure 3). The Envisioning Tool draws on the popular narratives from the future – the Science Fiction Films – to trigger the critical discussion about the possible future scenarios and implications behind scientific and technological development (link to the library: https://milastepanovic.wixsite.com/df4ct/explore-all). The creation of the cards was supported by data scraping tools (Seealsology and InData) and desk research. The analysis through the cards is aimed at suspending disbelief about the future, questioning why the popular narratives are perceived in that way, and how much they are relying on scientific facts. (Kirby, 2010)

Figure 3: Envisioning tool exploiting Science Fiction films (TICs on left, SICs on right) developed and designed by the author

Table 1 shows how the tasks are distributed throughout the Protocol for designing consciously to inform scenarios and which tools, theories, and methods are associated.

STAGE OF THE PROTOCOL	TASK	TOOL/METHOD/THEORY
1. Scraping and topic analysis	Translating Grand I Challenges into future Design Challenges.	EU agenda and SDGs, Societal Inspiration Cards – SICs (Author)
2. Building the agency and scaling the issue	Analyse the social and individual dimension of the future design challenge and interrelations between different actors involved in this scenario.	Social-ecological model (originally developed by Chicago School), Doughnut Economy Model (Raworth, 2017), and Actants Mapping Canvas (Sznel and Lewan, 2020).
3. Behavioural concern	Plan the user behavioural outcomes and identify behavioural design strategies.	Design with Intent (Lockton, Harrison and Stanton, 2010), Design for Sustainability Model (Loughborough University, 2017), Product Impact Tool (Dorrestijn, 2017), Functional triad (Fogg, 2009), Intention-Outcome matrix (Stibe and Cugelman, 2016)
4. Tech mediation	Anticipate the implications of the technology to trigger a	Technological mediation (Verbeek, 2006), Tech Inspiration Cards – TICs

	behavioural intervention translate behavioural design strategies into form and interactions (build mediations) of the product.	(Author)

Table 1: Stages, tools, methods and theories integrated into the Protocol for designing consciously

Methods

The research in question is established upon the Research Through Design (RtD) methodology, engaging the experts and users in the design research process and building the knowledge through making and interacting. (Zimmerman, Forlizzi, and Evenson, 2007) Bleeker et al. (2022) explain: "A prototype should set in motion constructive and collaborative investigation and debate, both through the process of its making and after the fact, as the design fiction circulates among its intended audience. […] Design Fiction should aspire to produce actionable provocations."

The author engages the experts in making processes and users as the audience to extend the discussion about the possible new interactions and artefacts to support sustainable behaviours. Researchers and designers can identify risks or untested assumptions through collaboration and mitigate them. In participatory practices, "Fictions have for instance been used when trying to elicit domain-specific insights from users, as in "Is this possible? What would happen if this technology/services/system was to exist?" (Lyckvi et al., 2018)

Research Through Design

Workshops with experts

The critical approach was applied in two workshops with experts (researchers and professionals) from different fields of study: Human-Computer Interaction (HCI), Behavioural Design, Digital Design, Sustainable Design, Neurosciences, and Social Psychology.

The objective of the workshops was to generate two envisioning scenarios (the year 2030) on the topics of Energy consumption and Water pollution. The workshops were held over two days (half a day each), and each workshop engaged different experts.

In Table 2 author reports some of the insights from the workshops used to generate scenarios.

TARGET BEHAVIOURS	PERCIEVED BARRIERS	BEHAVIOURAL STRATEGIES	TECHNOLOGY	PERCIEVED IMPLICATIONS
WATER DOUGHNUT				
Establish aware consumer behaviours to prevent water	Costs, infrastructure, perserving the desired behaviour	Communicating through metaphors, Real-time feedback,	Microplastic's Sensors, AR, Mobile app	Cognitive overwhelm, freedom of choice, data management

pollution through monitoring and dialogue with the environment.	long in time	Progress bars, Transparancy of the process, Kairos, Bundling, Possibility Trees		and transparancy, survelliance
THE ANIMAL				
Become independent in energetic sense through engagement of the community and implementation of new technologies.	How to create a democratic system to motivate everyone in the community to harvest and share energy.	Feedback through form, Communication through narratives, Transparancy of the process, Reciprocration	AI, AR, robotics, bioreactors	data management and transparency, Democratic use of energy (collection and sharing)

Table 2: Insights from the workshops with experts used to generate envisioning scenarios

Starting from the analysis conducted through the Protocol for designing consciously, experts and the author built the envisioning scenarios. The scenarios were structured in the following way:

1. Narrative part describing the World in 2030 in relation to the specific topic;
2. Technical and functional part describing the artefact: What is the artefact? What does it do? How does it work? How it interacts with the user? How and where is used?;
3. Analogies describing visually the artefact or the system of artefacts.

Figures 4 and 5 illustrate two envisioning scenarios generated by the experts and the author.

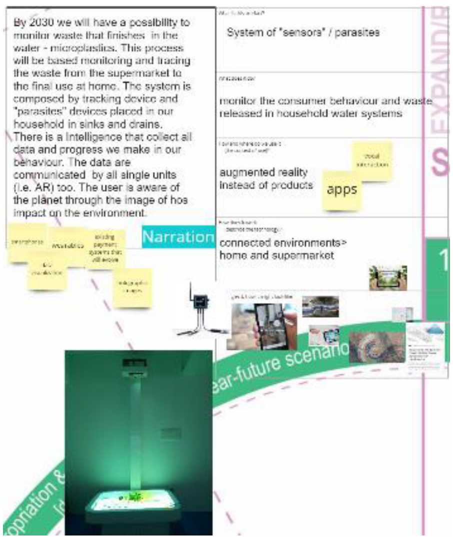


Figure 4: Envisioning scenario developed by the author in collaboration with experts on the topic Water Pollution

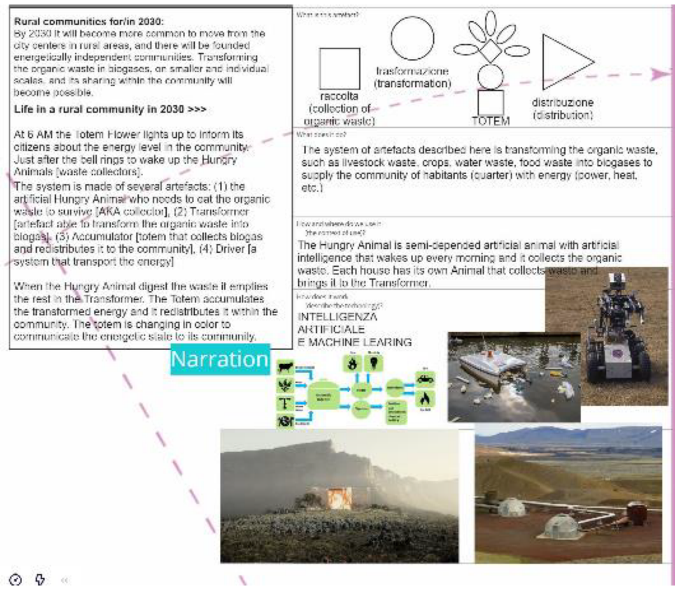


Figure 5: Envisioning scenario developed by the author in collaboration with experts on the topic Water Pollution

Design Fiction Prototyping: Two Design Fiction Prototypes to tackle sustainable behaviours toward Energy consumption and Water pollution

The prototyping activity took around one month and a half to complete the physical artefacts and postproduction (animated video).

Water Doughnut is a design fiction prototype tackling the issue of water pollution. The design challenge was to monitor the water waste from microplastics, from the shopping cart to the final use of products in households. The concept represents a device able to detect the presence of microplastics in chemicals used in a home environment, placing it in kitchen and bathroom sinks, bathtubs, dishwashers, and washing machines. The system consists of small devices embedding sensors and a mobile app to scan the chemical products and create product libraries and consumer stories based on their purchase. The device uses a holographic avatar which appears from the device and speaks to the user. The Avatar is a fictional animal that travels from the future to the present and explains to the user how microplastics impact the rivers, seas, and oceans and gives feedback about his/her behaviour to prevent negative outcomes. (Figure 6)

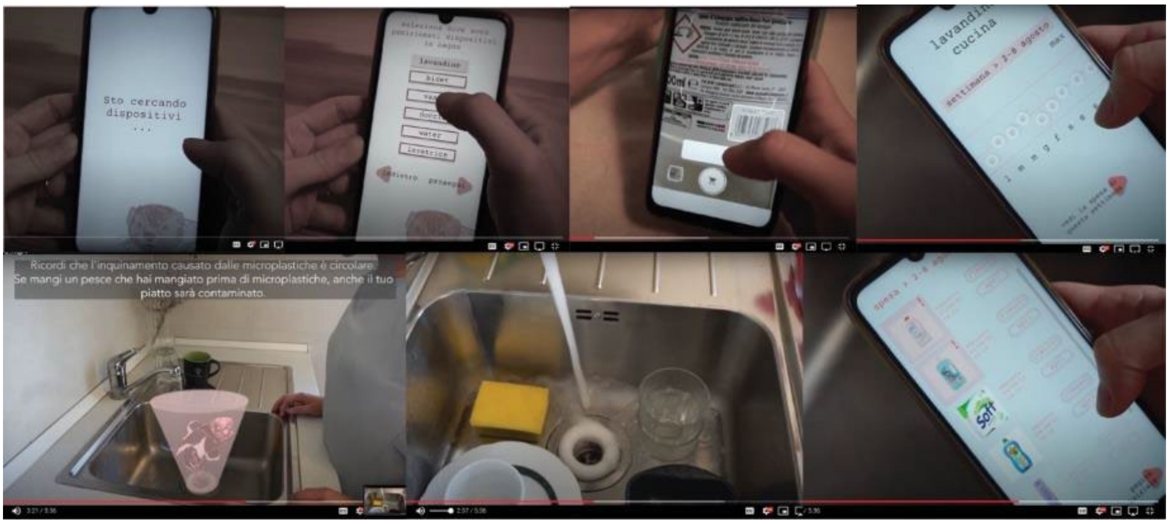


Figure 6: Water Doughnut Design Fiction Prototype: excerpts from the video https://youtu.be/xth5rB5Mrlk

The Animal is the second design fiction prototype tackling the issue of energy management and consumption. (Figure 7) The design challenge was reducing energy consumption through the new practices based on energetic independence. The scenario is about transforming organic waste into energy. This Design Fiction prototype explores how societies might change in the near future, moving toward rural areas and becoming independent in an energetic sense. The system consists of an independent robot for organic waste collection and a Totem for collecting the harvested waste and transforming it into energy for the community. The general idea is that each family has a sort of artificial Domestic Animal robot. Once the Animal is full, it goes to the Totem to fill it out. The Totem distributes the energy equally within the community. Besides, the Totem gives feedback about the energy to the community about the progress, distribution, and personal data to individuals.

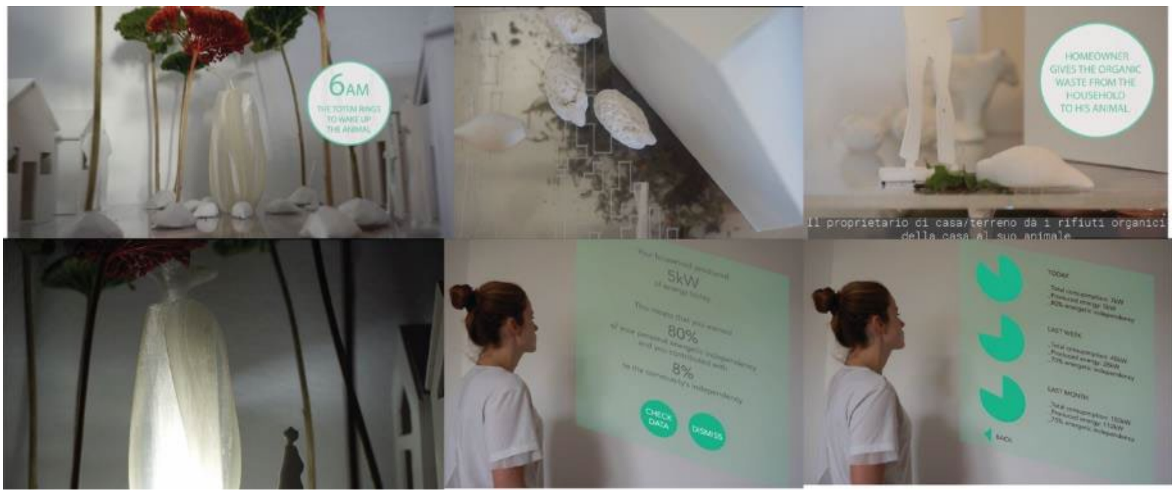


Figure 7: The Animal Design Fiction Prototype: excerpts from the video https://youtu.be/9XzDgswWcCw

Focus Groups

The focus group with users had as purpose to:

4. Understand whether the values and strategies prescribed by the experts are embedded in the fictional artefacts to leverage technological trustworthiness, prevent the barriers that may impact human behaviour, contextualize the technology within the social sphere;
5. Would these new interaction rituals and technologies support the users in becoming more environmentally aware and rethink their daily practices and habits?

The author conducted two focus groups in September 2021. The evaluation methods applied in focus groups were open discussion and semi-structured questionnaires. There were twenty-one participants (divided into two sessions) aged 25 to 43. The participants were mainly selected based on their age and interest in sustainability practices, and they needed to possess a minimum of digital literacy. The participants needed to be users of digital technologies but not necessarily advanced levels. The participants watched the design fiction prototypes, participated in an open discussion and completed semi-structured questionnaires. The sessions were registered. In both sessions, the structure of the questionnaire was the same. The first section of the questionnaire evaluated the prototypes' interaction and formal aspects. Here the author investigates the acceptability of the artefacts and technologies by the user and if there are any constraints or barriers in terms of interaction rituals and integration of these artefacts within the social sphere that may prevent the user from adopting sustainable behavioural patterns. The second section of the questionnaire evaluated the prototypes' technological aspects as the trustworthiness, privacy, functional reliability of the implemented technology, and relationship between the technology, user, and other actors present in the environment. The questionnaires were framed into twenty-two questions: closed questions (20%), open questions (20%), and quantitative evaluation of different aspects of the prototypes on a scale from 0 to 5 (60%). The quantitative results were calculated on the data set's average and compared to the open and closed question answers. The data gathered from the questionnaire were analysed together with the scripts generated from the registrations.

Results

The findings from the discussion and questionnaires aimed at helping the researcher extend the understanding of human behaviour in relation to the world and identify the most appropriate behavioural strategies and how to embed them into the formal and interaction aspects of technological artefacts.

The first focus group analysed and evaluated the Water Doughnut. The participants evaluated the interaction and formal aspects of this artefact as positive (evaluation 4,2/5). The participants appreciated, in particular, the part of the storytelling and the information provided by the avatar (metaphors). When it comes to the form of information provided by the artefacts, all the participants (100%) said that the relationship between the information (real-time feedback, progress bars, possibility trees) and action (behaviour to modify) was clear. Some parts of the mobile app were less comprehensive than others, like data about the level of microplastics released in the home and the possibility of monitoring the device in real-time through the app (4/5). Most participants (80%) stated that this artefact is slightly demanding to use, for two reasons. The first is that the mobile app is complex. The issue is also that they would need to have several devices all over the home to measure accurately the release of microplastics. The social and individual benefits of using this artefact were evident to 90% of participants. They recognised educational aspect of this artefact. When it comes to implications, participants claimed two potential issues. The first is the politics regarding the producers and chemical companies because if this artefact suggests acquiring based on “this is a good product” and “this is a bad product”. However, it depends on how the environmental regulations will evolve by that time. Regarding the behavioural aspects, all participants (100%) believe that such an artefact may help them adopt sustainable behaviours regarding the water pollution.

The second focus group analysed The Animal. Regarding the interaction and formal aspects of this artefact, the users evaluated it as relatively positive (3,9/5), and they found the artefacts’ functioning, feedforwards and feedback as comprehensive (4,4/5). Regarding the complexity of the artefact (general usability aspects of a system and service), more than half (60%) of the users did not find it demanding to use since the system is mainly autonomous; some of them found it slightly demanding (20%). In contrast, the rest (20%) found it demanding due to the maintenance and service concerns, integrating the Animal in the pedestrian zones, repair, and others. The fact that the users did not see any interface on the Animal made them bring some troubling conclusions, such as what if we need to turn it off for security reasons, but there is no way to interact; or what if the Animal is behaving in a strange, unexpected way and we do not know how to intervene. The users would like to establish a dialogue with the Animal because, according to them, it is risky to make it completely independent. All users agreed that the benefits are recognisable regarding the social and individual benefits. The benefits are particularly evident through the circularity of the system.

Discussion

Each of the two design fiction prototypes envision and anticipate a new application for the novel technology, scale and application for the existing technology, new interaction modalities and rituals, systems, services and products that could lead the users toward adopting more sustainable behaviours.

The open discussion with the users helped the author understand how to generate new guidelines or refine and appropriate the existing ones to design technological artefacts and interactions to support sustainable behaviours. The open discussion raised questions about the trustworthiness and reliability of some systems, such as the duration of the robot's autonomy and the fact that the system is entirely automated in The Animal.

In the case of the Water Doughnut emerged, some new questions and possible implications, such as the data collection and management, possible conflict of interest, and laws and policies regarding the chemical company's privacy, which were not embedded into the fictional artefact.

In both focus groups emerged new design spaces to explore further. For the Water Doughnut, users opened the possibility of monitoring the microplastics from the clothes – for instance, in the washing machine. The Animal triggered some ideas on how the communities could provide and facilitate the service to the citizens of rural communities.

Both the traditional and design fiction prototypes are means of communication, and they are both oriented toward the future – something that does not exist yet. Nonetheless, their purpose in design research and practice differ. Compared to traditional prototyping, defined mainly by technical problems and searching for solutions to implement in the real world, design fiction prototyping offers new ways to engage with the complexity and understand the user's lived experiences. These prototypes have nothing to prove or test in a functional sense, and they do not have the ambition of becoming 'real'. These prototypes are actionable. They aim to engage experts and users in probing the new possibilities and alternatives, considering possible blind spots or untested assumptions, risks, and how to mitigate them rather than generating solutions. (Bleeker, et al. 2022)

Compared to the other approaches, methods and tools addressing human behaviour, the critical approach with the Protocol for designing consciously and Envisioning Tool integrates a *pluriversal* perspective to analyse all the essential factors around sustainability, human behaviour, and technologies. The Protocol for designing consciously supports the analysis of human behaviour, sustainability, and the role of technologies through scaling the challenges and defining the actors engaged in building more thriving futures, the anticipation of negative behavioural outcomes and the ethical implications of technological implementation. Other tools and methods mentioned in this paper (i.e., Product Impact Tool, Design with Intent Tool, Functional Triad) provide a set of strategies and suggestions on how to integrate the technologies to support human behaviour. The critical approach differs from these tools because it is not framed around behavioural strategies. It proposes a new way of thinking about human behaviour and the environment in a larger context of events and actors to address the complexity and uncertainty.

However, it is important to note several issues the author faced and annotated during the design and research process, the time and skills needed to realise design fiction prototypes. Creating design fiction prototypes requires skills such as prototyping physical artefacts, video making, postproduction, and animation. The time of the prototypes' production may vary due to how much the researchers and practitioners are skilled in using such techniques, which may negatively impact the scalability and economy of such an approach.

Conclusions

Building on the knowledge from different disciplines and areas within and beyond the design research, the author generates a future-oriented critical approach with the Protocol for designing consciously and Envisioning Tool. The approach was applied in design and research activities with experts to generate envisioning scenarios addressing the Grand Societal Challenges and sustainable behaviours. The objective was to imagine and materialise new technological artefacts and interaction rituals that may support the user in adopting more sustainable practices.

In this paper, the author reports the results and insights from the focus group. The focus groups' results will be used to generate new design guidelines for designing technological artefacts to support sustainable behaviours. These guidelines may inspire the creation of new design spaces, appropriate the artefacts in terms of artefact-human-environment interactions, anticipate and prevent the possible ethical and societal implications of technologies, and prevent unintentional behavioural outcomes.

Further developments

Further development of this research will consist in completing the work on generating new design spaces and guidelines for design for sustainable behaviours. The upcoming research will apply these guidelines to a design and research of a new technological artefacts and services in present. At this stage, the idea is to move from the abstractness to concreteness to generate the action and inspire innovation in present. This will include design of new technological artefacts and measuring its' effectiveness in leveraging and sustaining the sustainable behavioural patterns in users long in time.

References

Auger, J. (2013). Speculative design: crafting the speculation, Digital Creativity, 24:1, 11-35, DOI: 10.1080/14626268.2013.767276

Berry, T. (1999). The Great World: Our Way into the Future, New York, Bell Tower

Bleeker, J. (2009). Design Fiction. A short essay on design, science, fact and fiction. Near Future Laboratory.

Bleeker, J. et al. 2022. The Manual of Design Fiction, Near Future Laboratory, Venice, Californa (USA)

Dorrestijn, S. (2017). The Product Impact Tool: Theories and Practices of Designing for Change. 10.4324/9781315576602-4.

Dunne, A., Raby, F. (2013). Speculative Everything: Design, Fiction, and Social Dreaming. MIT Press

Elsden, C. et al. (2017). On Speculative Enactments. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). Association for Computing Machinery, New York, NY, USA, 5386–5399. https://doi.org/10.1145/3025453.3025503

Escobar, A. (2018). Design for the Pluriverse. Radical Interdependence, Autonomy, and making of the Worlds*. Duke University Press*

Feenberg, A. (2005). Critical theory of technology: An Overview. Tailoring Biotechnologies, 1(1), 47–64.

Fogg, B. J. (2009). Creating persuasive technologies: an eight-step design process. Proceedings of the 4th International Conference on Persuasive Technology - Persuasive '09, 1. https://doi.org/10.1145/1541948.1542005

Grand, S., Wiedmer, M. (2010). Design fiction: a method toolbox for design research in a complex world. Designresearchsociety.Org, 1–25. https://doi.org/10.1145/1141911.1141937

Groth, C. et al. 2020. Conditions for experiential knowledge exchange in collaborative research across the sciences and creative practice, CoDesign, 16:4, 328-344, DOI: 10.1080/15710882.2020.1821713

Ilstedt, S., Wangel, J. (2014). Altering expectations: How design fictions and backcasting can *leverage sustainable lifestyles. In DRS (Design Research Society) 2014: Design's Big Debates- Pushing the Boundaries of Design Research. Umeå, Sweden, June 16-19 2014*

Jakobsone, L. (2017). Critical design as approach to next thinking. The Design Journal, 20 (sup1), S4253–S4262. https://doi.org/10.1080/14606925.2017.1352923

Kirby, D. (2010). The future is now: Diegetic prototypes and the role of popular films in generating real-world technological development. Social Studies of Science, 40(1), 41–70. https://doi.org/10.1177/0306312709338325

Lockton, D., Harrison, D. & Stanton, N. A. (2010). The Design with Intent Method: A design tool for influencing user behaviour, Applied Ergonomics, Volume 41, Issue 3, 2010, Pages 382-392, ISSN 0003-6870, https://doi.org/10.1016/j.apergo.2009.09.001.

Loughborough University Institutional Repository. (2017). Creating sustainable innovation through design for behaviour change: summary report (Vol. 91).

Lyckvi, S., et al. 2018. The role of design fiction in participatory design processes. In Proceedings of the 10th Nordic Conference on Human-Computer Interaction (NordiCHI '18). Association for Computing Machinery, New York, NY, USA, 976–979. https://doi.org/10.1145/3240167.3240258

Malpass, M. (2017). Critical Design in Context. History, Theory, and Practices. Bloomsbury

Niedderer, K. & Reilly, L. (2011). Research Practice in Art and Design: Experiential Knowledge and Organised Inquiry. Journal of Research Practice. 6.

Rapp, A., Tirassa, M., & Tirabeni, L. (2019). Rethinking Technologies for Behavior Change. ACM Transactions on Computer-Human Interaction, 26(4), 1–30. https://doi.org/10.1145/3318142

Raworth, K. (2017). Doughnut Economics: Seven Ways to Think Lika a 21st Century Economist. White River Junction, Vermont, Chelsea Green Publishing Rethinking Technologies for Behavior Change.

Stibe, A., Cugelman, B. (2016). Persuasive Backfiring: WhenBehavior Change Interventions Trigger Unintended NegativeOutcomes. Lecture Notes in Computer Science (2016): 65–77. ©2016 Springer International Publishin

Tanenbaum, J. T., Pufal, M. & Tanenbaum, K. (2016). Furious futures and apocalyptic design fictions: popular narratives of sustainability. interactions 24, 1 (January - February 2017), 64–67. https://doi.org/10.1145/3022123

Verbeek, P. (2006). Materializing Morality Design Ethics and Science, Technology and Human Values, 31(3), 361–380.

Zimmerman, J., Forlizzi,J. & Shelley Evenson. (2007). Research through design as a method for interaction design research in HCI. Conference on Human Factors in Computing Systems - Proceedings, January, 493–502. https://doi.org/10.1145/1240624.1240704

Mila Stepanovic

Mila Stepanovic (PhD) is an independent designer and researcher with a background in industrial design. Her research interest is design for sustainability, human behaviour, technologies, and future-oriented practices. In the last few years, she has collaborated on design and research projects at Politecnico di Milano and with Italian companies. She is teaching at Poli.design and collaborating as a teaching assistant at the Design School of Politecnico di Milano. Since 2017 she has been producing, contributing, and reviewing scientific publications and books, and she is a co-inventor of several patents. Beyond the design and research activity, she organizes and facilitates workshops on how to use the future to deliver more conscious designs of products and services. She exhibited her works at prestigious places like the Museum of Applied Arts in Belgrade, the Museum of Science and Technology Leonardo da Vinci in Milan, Human Factor Day in Milan, Maker Fair in Rome.

Materialization of the Future: The Demarcation Line between Prototypes and Demonstrators

Aleksandra Sviridova, University of Antwerp, Belgium
Jouke Verlinden, University of Antwerp, Belgium

Abstract

This paper describes the evolution of the concept of ‘design demonstrator’ in the field of industrial design which has been influenced by technological advancements and the increasing complexity of design problems. It compares it with the concept of ‘prototype’ from the perspective of the future conjecture. While both concepts aim to represent the designer’s imagination, there is a difference between them: unlike prototypes, demonstrators are conceptual in their focus and are used for communication purposes rather than evaluation (Bobbe *et al.*, 2023). In design research, prototypes and demonstrators are used for the opposite goals: converging and diverging the research area respectively, which is crucial for ‘designerly’ 2nd order cybernetics approaches, research THROUGH design and research AS design (inaccessible, inwards) (Chow and Jonas, 2008).
The study of demonstrators began with obtaining by the authors personal experiential knowledge through making a demonstrator for a client. The introspective reflection on it together with the analysis of an established set of demonstrators allowed them to narrow down the area of interest and formulate a working definition of a demonstrator as *at least a partially physical one-off design object that facilitates the interests of designer, client, user, and technology, and communicate them to the audience in an interactive way.* The authors suggest using the design practice perspective to study the conceptual nature of demonstrators and explore them as practice in line with associative, speculative, and critical design. This lens outlines the next direction of the research related to the aspect of ‘materialization of the future’.

Demonstrator; prototype; design research; inaccessible research; design practice

The most common understanding of the word 'prototype' is “the first of its kind — the first or preliminary model of something” (Sanders, 2013). In literature, it is a model used to describe, visualize, materialize, and test concepts to optimize them further until the desired result is achieved (Boeijen *et al.*, 2020; King and Chang, 2016). With time it expanded from an intermediate result that precedes the final product to an important actor in every step of the design process. Prototypes can be of different forms, and resolutions (Söderman, 2001), they can play different roles (Houde and Hill, 1997), be used as filters or manifestations of the design idea (Lim *et al.*, 2008), and address different objectives such as exploration, validation, specification, and communication (Verlinden, 2014).

If design is an assertion about the future and the design process is a formalized intention of making it certain, then prototypes are materialized steps on this way. In the late stages of the design process, they come very close to the final product. However, this is where the difference between them becomes blurry. During the work on Aramis, a guided transportation system developed in France, the engineers built five full-size capsules, a movable station, a control post, and a parking lot to check if their automatic coupling system works. Tests on a 1000m track and later, at the experimental station, were successful (RATP, n.d.). Engineers working on the project said that their prototype was ready to be launched on a bigger scale (Latour, 1996). However, Aramis never became part of the French transport system. If a prototype is 'preliminary', when does it become 'final'?

Figure 1. Aramis project in 1973 (left), 1980 (middle), and 1987 (right).

This question becomes even more difficult when the design challenge is abstract. In this case, designer does not have a predetermined direction and does not know if they are designing a device, a car, or a stand till the end of the ideation phase. How is it possible to build a prototype that resembles the future reality if we cannot even describe it, let alone estimate how successful the design will be? The design task becomes a task of exploration and opening up the space of solutions that never existed before. This is where prototypes become demonstrators, an emerging notion, combining engineering, art, and design.

The relationship between them, however, remains vague due to the lack of knowledge about demonstrators. In this paper, we will explore this relationship and highlight how it might contribute to design research.

The evolution of the concept of demonstrator

In the areas of industrial design and product development, prototypes are mostly physical: sketches, foam and paper mock-ups, clay models, etc., and the role they play usually depends on the stage of the project. Prototypes can serve as a basis for comparison of different design directions, reveal the context of use, support thinking, serve as a memory device, test design behavioral hypotheses, detects modeling discrepancies and errors, distill key parameters of interaction, and locate limits of use (McGarry, 2005). Prototypes are integral to the communication of the design product to team members, client, manufacturer, or its potential user. In these roles, prototypes are typically tailored to a specific group of people, such as a client or a user. As a result, they may significantly vary in their scope or resolution. However, when it is needed to communicate between multiple stakeholders and it becomes crucial to ensure that the message is conveyed clearly, prototypes might be ineffective. In fact, to serve as a medium, prototypes have evolved into a bunch of new concepts.

Technology demonstrations have become necessary to effectively communicate advanced technology to the broader audience, they serve to showcase the performance of various components and systems, as well as validate their effectiveness. As instruments of participatory discussion and exploration, prototypes advanced to provotypes and critical artifacts (Mogensen, 1992). A prototypical project that combines technical challenge with societal relevance to achieve radical improvements is known as a moonshot (Casadevall and Fang, 2016; Purmal *et al.*, 2016). Finally, there are demonstrators, that combine a little bit of everything in order to better convey and facilitate the message included (Moultrie, 2015). Recent studies notice though, that the difference between these concepts is operational: while prototypes are built to evaluate a hypothesis, the main goal of demonstrators is to communicate it (Figure 2)(Bobbe *et al.*, 2023).

Figure 2. The continuum between prototypes and demonstrators (see Bobbe et al., 2023).

Historical cases

We trace the origin of the term back to the 1960s to the famous “Demo or die!” when researchers at MIT Media Lab were looking for new ways of implementing innovative technology. They built demonstrators to show how their proposed solution should work so that everybody could experience it first-hand. The results could still be considered prototypes, as they were not meant to be manufactured and distributed to the general public, but they were also something more. The main innovations in their designs were not the products themselves, but the ways *how* to utilize new technology. The resulting objects were simply the embodiments of these scenarios. For example, a digital newspaper NewsPeek was the answer to the question “how can digitalization or VR change media?” It consisted of text blocks with highlighted areas that could provide personalized information on click (Media Lab, 1986); Dogmatic proposed how storytelling can work in highly immersive virtual reality, leaving the viewer to choose the direction of their experience (Figure 3)(Brand, 1988; Media Lab, 1995; Media Lab archive, n.d.). In addition to combining the previously unfamiliar digital realm with more customary analog processes, researchers also introduced concepts such as interactivity, accessibility, and information distribution. By opening multiple discussions, these demonstrators also explored the economic, moral, and philosophical aspects of free and ubiquitous information.

In literature, the meaning of demonstrators primarily revolves around choosing the best technology to implement. They are a logical step between building a full-scale prototype and moving into production after estimating all costs and risks of using new technology.

Figure 3. Newspeek (left) and Dogmatic (right) projects by MIT Media Lab.

Demonstrators are often carefully designed in research labs. For example, D1244, a high-rise building, was constructed at the University of Stuttgart specifically to test twelve types of façades under real conditions (2021). It is equipped with monitoring and adapting systems of sensors and actuators, that can detect and mitigate a wide range of disturbances. However, the building does not serve any other purpose besides demonstrating the reduction of maintenance resources. The goal of such projects is to evaluate the readiness of the technology to be applied in the industry. Therefore, researchers, studying technology demonstrators (or technology demonstrations, this term often can be found in literature), focus on aspects that facilitate this evaluation, such as performance and market acceptance (Stelvaga and Fortin, 2022).

In turn, designers come to the development of demonstrators intuitively. Thus, exemplars that are found in portfolios of design studios are rarely called that. Design demonstrators (we introduce this term to distinguish another facet of the concept) often contain a complex story to tell. L'Artisan Électronique, a virtual pottery wheel designed by studio Unfold proposes a solution for digital making as well as explores the intersection between craft and industry (Figure 4) (Unfold Design Studio, 2010). Not only keep a beginner their hands clean while making a beautiful vase, but also they can ponder if this technology enhances craftsmanship or detracts from it.

Figure 4. The facade (left) and the actuators' room (middle) of D1244 by the University of Stuttgart and l'Artisan Électronique by Unfold (right).

Demonstrators as sources of experiential knowledge

Chow and Jonas highlight a second order cybernetic perspective in research methods, which represents a shift from an analytical perspective towards an experiential one (Table 1)(2008). However, to position themselves inside the design system, the researcher needs a skill set that differs from their usual non-interventional approach and includes empathy and intuition. With empathy, designers can connect to the design system, and collect and incorporate experiential data into the research process (Gasparini, 2015), while intuition navigates them through complex dynamic factors of it (Badke-Schaub and Eris, 2014).

Design practice here plays both exploratory and confirmatory roles. Prototypes can give direction to new scientific knowledge (Stappers and Giaccardi, 2017), be a vehicle for theory building (Koskinen *et al.*, 2011), and help establish critical areas of concern and judgment (Gaver, 2012). Due to their complex nature, demonstrators can be used as sources of tacit knowledge (Sviridova *et al.*, 2022a).

Observer position ● Observer looking ⟶	Outside the design system (1st order cybernetics)	Inside the design system (2nd order cybernetics)
outwards (convergence)	research FOR design	research THROUGH design
inwards (divergence)	research ABOUT design	research AS design (inaccessible)

Table 1 The concepts of research in design according to the observer position (see Chow and Jonas, 2008).

Prototypes are undoubtedly important parts of the process of developing a demonstrator. In our experience, though, the conditions and needs of making them are also intuitive. Probably, it happens due to the lack of knowledge of how to make a demonstrator. Fortunately, this lack of information can potentially lead to insights into the development of demonstrators if properly reflected. Schön talks about reflection on action that should happen after something was made to track intuitively made decisions and try to study their reasons and potential scenarios that were rejected during the thinking process (Schön, 1984). In other words, every time we make a prototype while working on a demonstrator, we should stop for a moment to ask ourselves what we are struggling with or what we are trying to test.

Developing tools for conducting such research can potentially unlock access to the designer's state of mind during the design process and the decision-making process that usually happens intuitively (Albers and Wiedner, 2011). These tools can reconnect designers with their experiential knowledge and bridge the gap between practice and theory (Figure 5). As this area is highly ambiguous, we look towards introspective practices and methods used in psychology that focus on subjective experience and can support the understanding of tacit aspects of creativity. Autoethnography can be helpful to track the design process and reflect on the connection that this process establishes with the designed object (Triantafylli and Bofylatos, 2019).

Psychology, in turn, offers a variety of methods, unorthodox for design research yet potentially helpful as they help people communicate with their inner voice. For example, designers use empathy during the design process to consider the perspectives of different stakeholders to come up with an optimal solution. Methods that help designers reconnect with these perspectives such as Internal Family Systems (Schwartz, 1995; Sviridova *et al.*, 2022a) can uncover implicit guiding principles, value systems, and enablers.

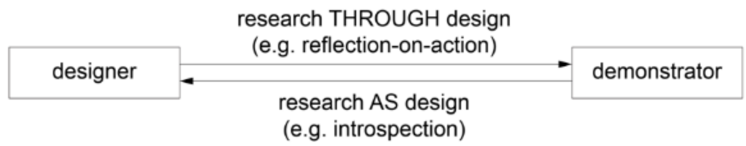


Figure 5. Areas of design research that demonstrators might enhance.

Without a clear understanding of what can be called a demonstrator and what cannot, it was impossible to collect enough exemplars for analysis and develop appropriate questions to interview designers who have worked on demonstrators intuitively. Therefore, to resolve the problem of a chicken and an egg, it was decided to first gain personal knowledge through design practice (Mäkelä, 2007). The authors of this paper were involved in the creation of a demonstrator for a client that has been already introduced to this notion. They developed an original optimization algorithm and wanted to explain its benefits to their potential customers, mostly chief officers in related companies, during the annual expo. Since the algorithm is pure mathematics and the audience was no experts in this area, the designers decided to focus on the application of the algorithm in several scenarios. To show the benefits and downsides of using their advanced method of optimization in comparison with the current one, the designers depicted both of them as competing cars. The result was a stand of two parts: a cabinet with a projector and a wall with physical relief, that resembled a famous local race track. The animation projected onto it demonstrated how the process of optimization depends on a possible scenario and how it influences the speed of the car and the distance it can cover. An expert from the client side would give more details during the animation (Figure 6, Figure 7).

Figure 6. The process of adjusting the projection (left), the finished stand (middle), and the process of milling the relief (right).

Figure 7 The animation that was projected on the relief (left) and the source video (right).

While working on the project, the designers made the decisions regarding this project intuitively. They have obtained expert knowledge on what a demonstrator should and should not be like, however, they could not articulate it. Unrolling back their design process, they noticed that they learned about the processes of sending and receiving messages as well as the role of tangible, visual, and audial aspects of them (Sviridova *et al.*, 2021). Through this subjective experience, the researchers were able to formulate a working hypothesis that e*xperts from research labs and independent design studios (not only working for client projects) obtain tacit knowledge of the characteristics of demonstrators that are sufficient to distinguish them from other design outcomes.* In addition, they obtained a lens that allowed the selection of the experts for an interviewing.

Finding common ground

Being involved in the process of making an artifact gave a great boost to the research, providing it with experiential rich knowledge. This knowledge was implicit and subjective, therefore, hard to translate and generalize. In other words, the knowledge obtained was based on recognition and perception (*knowing*) without static knowledge (*knowledge*) (Mareis, 2012). However, when knowledge is internalized, it can be perceived as ‘intuition’ and can be demonstrated. According to Polanyi, we comprehend the entity by relying on our awareness of its particulars. Thus, if something has joint meaning to us, it is possible to detect its parts, for example, by methods of observations or associations (Polanyi, 1974).

Thus, the next step was interviews with three experts, people who use the word “demonstrator” in their design practice. As they also bore only tacit knowledge of what a demonstrator is, repertory grid interviews were chosen to extract it. This method is used to get a description of how a person views the world, in their own terms. It is especially efficient in capturing professionals’ realm of discourse without contaminating it with the interviewer’s viewpoint (Jankowicz, 2003).

Participants were asked to form a set of projects that they considered to be demonstrators. They were then presented with three randomly selected elements from their chosen sets and asked to describe what the first two elements had in common, as opposed to the third element. Based on their responses, the remaining elements were then rated according to the identified constructs. This approach is based on the

Personal Construct Theory by Kelly, which posits that a person's reality is built upon contrasts rather than absolutes (1991).

Each set consisted of 8-10 elements based on examples suggested by the interviewer. However, most of the elements were added by the participants. Surprisingly, the sets only partially overlapped and there was not a single element that was present in all three sets. The analysis showed that each participant's repertoire — a list of constructs — highlighted a different aspect of what a demonstrator is (Table 2). These aspects were: technology, aesthetics, and communication. The only thing all three experts talked about was the tangibility of a demonstrator, although, each of them meant a certain aspect of it: the physicality of the object itself, the interaction it provides, or the tangibility of the message demonstrator conveys.

Although it was still difficult to formulate direct questions for further interviews, the results of repertory grids provided insights for further steps of the research. The researchers were able to narrow down the area of interest by focusing on certain aspects, which were used as lenses to explore the importance of sensual and spiritual experience, appearance, and storytelling in designing demonstrators.

1st expert	2nd expert	3rd expert
ethereal — static, solid, material	digital — physical interaction	(talking about) tangible — (talking about) intangible
design- — engineering-driven aesthetics	environment — object	conflict — harmony
speculative open-ended — descriptive	individual — social interaction	facts involved — emotional

Table 2. Examples of constructs elicited by the experts.

Perspectives and directions of demonstrators

Finally, a unified set of proposed demonstrators was analyzed, leading to the formulation of the four characteristics of a demonstrator, namely: 1) they convey a message; 2) they are designed for exposure; 3) they reflect the present, and 4) they are finished products (Sviridova *et al.*, 2022b). These characteristics portray a very broad scope of demonstrators, including those that are closer to art objects, technology demonstrations, or advertisement projects (Figure 8). For research purposes, we narrow it down to product development and industrial design and will refer to it as 'design demonstrators'.

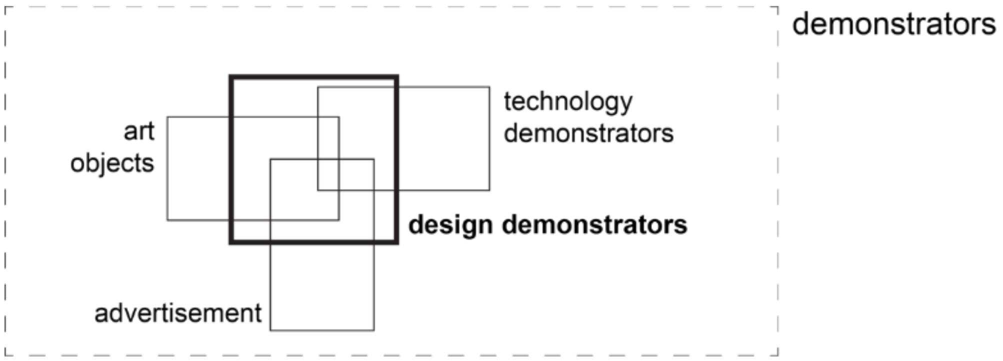


Figure 8 A set of demonstrators with subsets of art objects, advertisement projects, technology demonstrators, and demonstrators in product development.

Demonstrators can support designers in reflecting on their design activities and exploring new design spaces; furthermore, they are used as boundary objects during the development process to mediate communication between stakeholders (Smulders et al., 2008). Although, the understanding of boundary objects vastly differs from a material object to a word or even the Beatles(Star, 2010), on an organizational level even design can be considered as an interactive boundary object (Tharchen *et al.*, 2020). There is a discrepancy regarding their nature: when social sciences believe that boundary objects cannot be created, they only become ones when they establish a shared knowledge or context among different social groups (Carlile, 2002); other disciplines believe they can be made during participatory research (Groot and Abma, 2021). We believe boundary objects can be built as a result of design activity and a particular way of facilitation is established during the design process, meaning, demonstrators can be designed in a particular way to serve as efficient boundary objects.

Definition

Making a demonstrator may be the best way to understand the notion, but we still need to develop a common language to have a constructive discussion. Thus, in product development and industrial design, we define a demonstrator as *at least a partially physical one-off design object that facilitates the interests of designer, client, user, and technology, and communicate them to the audience in an interactive way*.

In this definition, the designer is someone who designs a demonstrator, which involves responsibility for both its appearance and functionality; the client is the individual who initiates the creation of a demonstrator, providing a reason or purpose for it (the client and the designer can be one person); the user is someone who is supposed to be interacting with a demonstrator, someone who designer has in mind when designing the ergonomics, usability, use case scenario, etc.; technology in its broadest understanding plays a crucial role in 'thingifying' an idea and transforming it to an object; the audience is those people who will eventually interact with the demonstrator and are the target of its message (such as visitors of the exhibition, policymakers, or fundraisers); finally, interaction refers to the dialogue created between a person and the demonstrator. This dialogue is both physical and emotional and is manifested through the interplay between form, function, and technology over time.

This combination of actors is very similar to those in prototypes, however, there is a difference. First of all, prototypes are mere milestones on the way to the final result. They manifest a certain aspect of a design solution with a certain detailing. High-resolution prototypes resemble a finished product and may serve more as a means of communication. In the case of novel technology, they would also address intangible aspects of it, such as user experience, social acceptance, or temporal effects. This is where the difference between the two notions becomes blurry and causes confusion.

However, there is a very important actor in this scheme (Figure 9) that brings demonstrators closer to social sciences than engineering. Prototypes can be made solely for the designer, if they quickly need to test an idea, or explore possible forms, while demonstrators are always presented to the audience. Moreover, the message that this audience should be able to receive and interpret, often can be transferred in a form of a presentation slide or an explainer interview. However, clients and designers choose a more interactive tangible representation, which connects demonstrators with the definition of New media given by Rice. He claims that studying new hardware technologies is necessary to study 'interpersonal, intercultural, organizational' and other types of communication (Rice, 1984). He also argues for empiric and experiential investigations of behaviors and impacts, building upon McLuhan's idea that 'understanding of social and cultural range is impossible without a knowledge of the way media works as environments' (McLuhan and Fiore, 1967). In this regard, studying demonstrators is another step in joining the worlds of communication and engineering research.

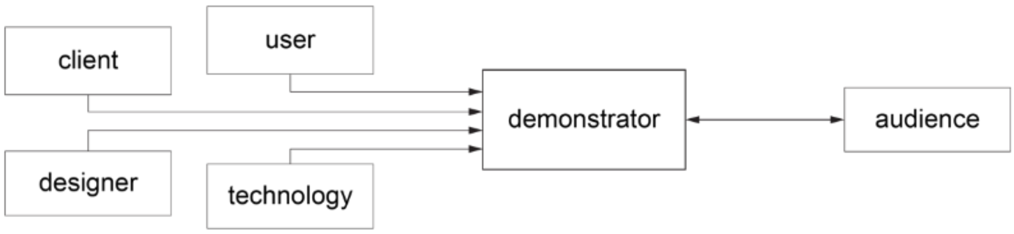


Figure 9. Actors, involved in the development process and the process of use of demonstrator.

Demonstrators are material implementation of stories that could happen right now, at the current technological level. They are objects of design fiction, described by Bleecker as "a conflation of design, science fact, and science fiction" (Bleecker, 2009). Demonstrators bring real experience, such as a ride on a 3d-printed metal bike (Boruslawski, 2016), assembling parts in augmented reality (ground-eight.com, n.d.), or demining a region with a large wind toy (Minekafon.org, n.d.) even if they are, in fact, fictional: 3d-metal printers are far from domestic use, the range of details one can assemble is limited, and a giant tumbleweed is highly ineffective (Figure 10). Yet, designing allows us to imagine the future, criticize and reflect on what we have now, and suggest desirable scenarios. Demonstrators unite speculation with pragmatism, stimulating discussion that applies to a wide audience and opening up diverse communication, technological, and societal problems.

Figure 10. Arc Bike by MX3D (left), AR Headset by Ground Eight (middle), and Mine Kafon by Massoud and Mahmud Hassani (right).

We find demonstrators to be in-between the space between “proto” and “real” as they resemble an idea yet do not aim to become an industry standard. A boundary object that can be designed, unlike the common interpretation of Star’s concept, to decrease the distance between the user and the innovation and start a discussion about how we can benefit from it.

Demonstrators as design representations

Unlike prototypes, demonstrators are conceptual in their focus. They are designed for a general audience and aim to draw attention to a certain topic, although, in a quite broad sense. That said, they can be studied as an alternative practice to traditional industrial design, in line with critical design practice. Introducing the notion of critical design, Dunne argues how it is different from art, yet dependable on it, because “to bring object function as criticism, one must move closer to the world of fine art” (Dunne, 1999), just like demonstrators are different yet dependable on prototypes. He attributes it to the difficulty of conducting such research within the design profession. Indeed, at that time design research was trying to find its way within a scientific paradigm, denying designerly ways of knowing through making until Jones admitted that it needs professionals with developed skills of intuition and informed knowledge to challenge the increasing level of complexity of problems (1992).

Malpass identifies three categories of critical practices: associative, speculative, and critical (2017). They differ in what they focus on, the method they use to tell the narrative, and how far they look into the future. Critical design focuses on present social, cultural, and ethical implications and through mechanisms of defamiliarization extends the distance from the designer to the viewer, leaving him a space for interpretation. Speculative design puts scientific and technological trends in everyday context to explore the role industrial and product design plays in bringing innovations to our houses. Lastly, associative design is directed towards design as a discipline in order to challenge current design norms by questioning their methods, traditions, and values.

Design for demonstrators focuses on a message to convey to the audience. Unlike critical and speculative design, this message is not a critique but rather a proposal. While both practices look into the distant future and warn of potential consequences, demonstrators focus on the present tools available and offer practical solutions for discussion. Malpass ranges critical practices by the type of satire they use to better convey the proposed scenario from a subtle Horatian to a strong Juvenalian. The first operates through mild humor and parody while the latter is more contemptuous and allegorical (Malpass, 2017). Putting demonstrators at the beginning of this row, we would say they use optimistic provocation since their goal is to shorten the distance between the problem and the audience through the proposed solution (Figure 11).

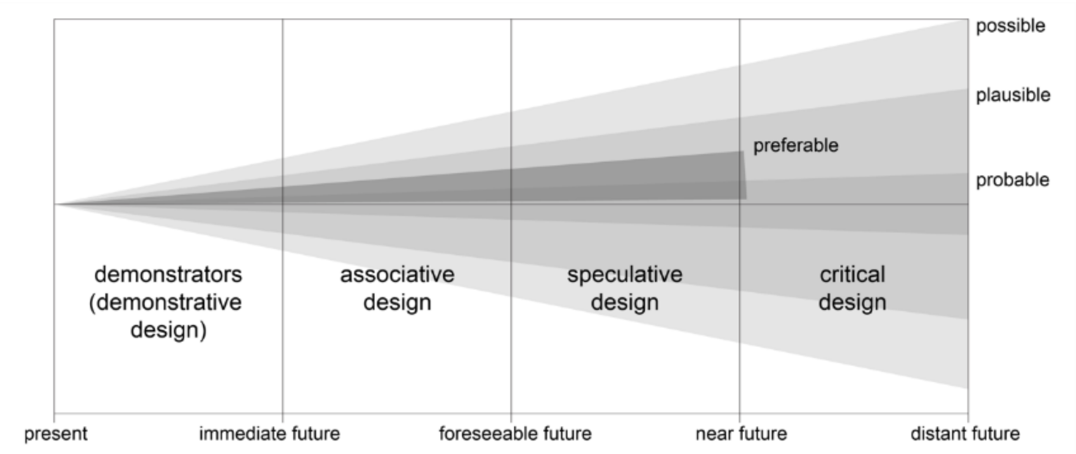


Figure 11. Demonstrators on the timeframe of critical design practices. Based on Dunne and Raby (2013).

Not surprisingly, the research of critical practices comes from practice to theory. It is necessary to have a critical number of objects to develop a theoretical underpinning. Needless to say, it was essential to formulate a preliminary definition of demonstrators to start forming a valid repository. Thus, in the future other aspects of demonstrators could be identified.

Discussion and conclusions

While the notion of 'demonstrator' has historically developed from that of the 'prototype', it is important to formulate the difference. The demarcation line between them lies where the expected outcome shifts from focusing on one aspect of the design solution to the conceptual environment around it. In between lays the spectrum of 'technological demonstration', which may be too general to be called a prototype yet not interactive and storytelling-driven enough to be considered a demonstrator. While it is important to recognize the difference between these concepts, we believe it is also important to study demonstrators from the perspective of conceptual design practice, in line with associative, speculative, and critical design.

To understand how demonstrators can address complex design problems and contribute to design research, it is first necessary to frame them within the design research context through insights gained by personal experience, expert knowledge, and analysis of a set of examples. They were defined as at least partially physical one-off design object that facilitates the interests of designer, client, user, and technology, and communicate them to the audience in an interactive way.

Prototypes and demonstrators aim to assert about the future: prototypes materialize 'a thing', demonstrators — 'about a thing'. Both concepts are rather mysterious as they try to depict something that never existed before and will never exist in exactly the same as the depicted way in the future. However, designers use empathy and intuition to establish the necessary actions, which, if carefully followed, make their design a reality. Researchers can follow their lead to study these not-yet-made steps resulting in not-yet-existed objects. Demonstrators and prototypes can both be tools for it, replacing and complementing each other depending on whether the research scope needs to be focused or expanded.

The use of prototypes in design research narrows the scope down, while demonstrators open it up. The potential use of both notions in the development of the second generation of design research methods, namely ‘research THROUGH design’ and ‘research AS design’, lies in studying the experiential and intuitive knowledge obtained by designers during the process of developing demonstrators. To develop appropriate tools for this, we believe the research should advance in studying how to apply methods of introspection. In addition to that, in our future research, we will try to identify and study the components of demonstrators and their design process based on the given definition.

References

Albers, A. and Wiedner, A. (2011), “Analysis of created representations of the design object during the problem solving process”, *ICED 11 - 18th International Conference on Engineering Design - Impacting Society Through Engineering Design*, Vol. 1 No. August, pp. 256–265.

Badke-Schaub, P. and Eris, O. (2014), “A Theoretical Approach to Intuition in Design: Does Design Methodology Need to Account for Unconscious Processes?”, in Chakrabarti, A. and Blessing, L.T.M. (Eds.), *An Anthology of Theories and Models of Design*, Springer, London, pp. 353–370.

Bleecker, J. (2009), “Design Fiction: A Short Essay on Design, Science, Fact and Fiction”, *Near Future Laboratory*, available at: https://shop.nearfuturelaboratory.com/products/design-fiction-a-short-essay-on-design-science-fact-and-fiction (accessed 24 January 2023).

Bobbe, T., Opeskin, L., Lüneburg, L.M., Wanta, H., Pohlmann, J. and Krzywinski, J. (2023), “Design for communication: how do demonstrators demonstrate technology?”, *Design Science*, Cambridge University Press, Vol. 9, p. e3.

Boeijen, A. van, Daalhuizen, J. and Zijlstra, J. (2020), *Delft Design Guide*, BIS Publishers, available at: https://www.bispublishers.com/delft-design-guide-revised.html (accessed 25 January 2023).

Boruslawski, P. (2016), “TU delft students use MX3D robots to 3D print stainless steel arc bicycle”, available at: https://www.designboom.com/technology/tu-delft-arc-bicycle-mx3d-02-04-2016/ (accessed 27 January 2023).

Brand, S. (1988), *The Media Lab: Inventing the Future at M. I. T.*, Reprint ed., Penguin Books.

Carlile, P.R. (2002), “A Pragmatic View of Knowledge and Boundaries: Boundary Objects in New Product Development”, *Https://Doi.Org/10.1287/Orsc.13.4.442.2953*, INFORMS, Vol. 13 No. 4, pp. 442–455.

Casadevall, A. and Fang, F.C. (2016), “Moonshot Science—Risks and Benefits”, *MBio*, American Society for Microbiology 1752 N St., N.W., Washington, DC, Vol. 7 No. 4, available at:https://doi.org/10.1128/MBIO.01381-16.

Chow, R.W. and Jonas, W. (2008), “Beyond Dualisms in Methodology: An Integrative Design Research Medium ‘MAPS’ and some Reflections”, in Durling, D., Rust, C., Chen, L.-L., Ashton, P. and Friedman, K. (Eds.), *Undisciplined!*, Sheffield Hallam University, available at: http://digitalcommons.shu.ac.uk/drs2008/session10/track_b/2.

Dunne, A. and Raby, F. (2013), “Speculative Everything”, *The MIT Press*.

Gasparini, A.A. (2015), “Perspective and use of empathy in design thinking”, *ACHI 2015 -*

8th International Conference on Advances in Computer-Human Interactions, No. March, pp. 49–54.

Gaver, W. (2012), “What should we expect from research through design?”, *Conference on Human Factors in Computing Systems - Proceedings*, No. May 2012, pp. 937–946.

Groot, B. and Abma, T. (2021), “Boundary objects: Engaging and bridging needs of people in participatory research by arts-based methods”, *International Journal of Environmental Research and Public Health*, MDPI, Vol. 18 No. 15, available at:https://doi.org/10.3390/IJERPH18157903.

ground-eight.com. (n.d.). “AR Headsets in Assembly Workspaces”, available at: https://ground-eight.com/work/ar-headsets-in-assembly-workplaces/ (accessed 27 January 2023).

Houde, S. and Hill, C. (1997), “What do Prototypes Prototype?”, *Handbook of Human-Computer Interaction*, North-Holland, pp. 367–381.

Jankowicz, D. (2003), *The Easy Guide to Repertory Grids*, J. Wiley, available at: https://www.wiley.com/en-be/The+Easy+Guide+to+Repertory+Grids-p-9780470854044 (accessed 24 January 2023).

Jones, J.C. (1992), *Design Methods*, 2nd ed., Wiley.

Kelly, G. (1991), *The Psychology of Personal Constructs*, Routledge in association with the Centre for Personal Construct Psychology, available at: https://www.routledge.com/The-Psychology-of-Personal-Constructs/Kelly/p/book/9780415037990 (accessed 24 January 2023).

King, S. and Chang, K. (2016), *Understanding Industrial Design*, O’Reilly Media, Inc., available at: https://www.oreilly.com/library/view/understanding-industrial-design/9781491920381/.

Koskinen, I., Zimmerman, J., Binder, T., Redström, J. and Wensveen, S. (2011), *Design Research Through Practice: From the Lab, Field, and Showroom*, Morgan Kaufmann.

Latour, B. (1996), *Aramis, or the Love of Techonlogy*, Harvard University Press, available at: https://www.hup.harvard.edu/catalog.php?isbn=9780674043237 (accessed 25 January 2023).

Lim, Y.K., Stolterman, E. and Tenenberg, J. (2008), “The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas”, *ACM Transactions on Computer-Human Interaction*, Vol. 15 No. 2, available at:https://doi.org/10.1145/1375761.1375762.

Mäkelä, M. (2007), “Knowing Through Making: The Role of the Artefact in Practice-led Research”, *Knowledge, Technology & Policy*, Springer Science and Business Media LLC, Vol. 20 No. 3, pp. 157–163.

Malpass, M. (2017), *Critical Design in Context*, Bloomsbury Academic, available at:https://doi.org/10.5040/9781474293822.

Mareis, C. (2012), “The Epistemology of the Unspoken: On the Concept of Tacit Knowledge in Contemporary Design Research”, *Design Issues*, MIT Press, Vol. 28 No. 2, pp. 61–71.

McGarry, B. (2005), *Things to Think With: Understanding Interactions with Artefacts in Engineering Design*, The University of Queensland.

McLuhan, M. and Fiore, Q. (1967), “The Medium is the Massage: An Inventory of Effects”, *Gingko Press*, Gingko Press, Vol. 1, p. 159.

Media Lab. (1986), “MIT Media Lab documentary, 5: NewsPeek - YouTube”, available at: https://www.youtube.com/watch?app=desktop&v=M1tJ7qFAG2Q (accessed 26 January 2023).

Media Lab. (1995), “music for ‘Dogmatic’ Demo MIT Media Lab 1995 - YouTube”, available at: https://www.youtube.com/watch?v=U3muAowpUE8 (accessed 26 January 2023).

Media Lab archive. (n.d.). “25 years of Electronic Publishing”, available at: https://web.media.mit.edu/~walter/ep.html (accessed 22 January 2023).

Minekafon.org. (n.d.). “Mine Kafon”, available at: https://minekafon.org/index.php/mine-kafon-ball/ (accessed 27 January 2023).

Mogensen, P.H. (1992), “Towards a Provotyping Approach in Systems Development”, *Scand. J. Inf. Syst.*, Aarhus University Library, Vol. 21 No. 412, available at:https://doi.org/10.7146/DPB.V21I412.6725.

Moultrie, J. (2015), “Understanding and classifying the role of design demonstrators in scientific exploration”, *Technovation*, Elsevier, Vol. 43–44, pp. 1–16.

Polanyi, M. (1974), *Personal Knowledge*, University Of Chicago Press, available at: https://www.amazon.com/Personal-Knowledge-Towards-Post-Critical-Philosophy/dp/0226672883.

Purmal, K., Goldman, L. and Janzer, A. (2016), *The Moonshot Effect: Disrupting Business as Usual*, Wynnefield Business Press, available at: https://books.google.be/books?hl=en&lr=&id=c9J2DAAAQBAJ&oi=fnd&pg=PT7&dq=+The+Moonshot+Effect:+Disrupting+Business+as+Usual&ots=9QIcQ5msN2&sig=_VevgjXvPhCqslxLJZ3ho_GToQs&redir_esc=y#v=onepage&q=The Moonshot Effect%3A Disrupting Business as Usual&f=false (accessed 19 January 2023).

RATP. (n.d.). “Le métro, c’est automatique !”, available at: https://youtu.be/BxF7W2IBejY (accessed 26 January 2023).

Rice, R.E. (1984), *The New Media: Communication, Research, and Technology*, SAGE Publications Inc.

Sanders, L. (2013), “Prototyping for the Design Spaces of the Future.”, in Valentine, L. (Ed.), *Prototype. Design and Craft in the 21st Century.*, Bloomsbury Academic, pp. 59–74.

Schön, D. (1984), *The Reflective Practitioner: How Professionals Think In Action*, Basic Books.

Schwartz, R.C. (1995), *Internal Family Systems Therapy*, Guilford Press.

Söderman, M. (2001), “Product representations: Exploring computer-based technologies and customers’ understanding of product concepts”, *Doktorsavhandlingar Vid Chalmers Tekniska Hogskola*.

Stappers, P.J. and Giaccardi, E. (2017), “Research through Design | The Encyclopedia of Human-Computer Interaction, 2nd Ed.”, *The Encyclopedia of Human-Computer Interaction*, available at: https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/research-through-design (accessed 19 January 2023).

Star, S.L. (2010), “This is not a boundary object: Reflections on the origin of a concept”, *Science Technology and Human Values*, Vol. 35 No. 5, pp. 601–617.

Stelvaga, A. and Fortin, C. (2022), “Development of a Methodology for Technology Demonstration Projects Evaluation”, *Proceedings of the Design Society*, Cambridge University Press, Vol. 2, pp. 273–282.

Sviridova, A., Everaerts, S., Tas, L., Yachchou, S., van Hoofstat, L. and Verlinden, J. (2021), “The Role of Auditory Description in Comprehension of Demonstrators: A Pilot Study”, *Advances in Creativity, Innovation, Entrepreneurship and Communication of Design*, Vol. 276, Springer, Cham, pp. 530–538.

Sviridova, A., Stokhuijzen, D. and Verlinden, J. (2022a), “Accessing the Inaccessible:

Demonstrators as Sources of Tacit Knowledge", *Proceedings of the Design Society*, Cambridge University Press, Vol. 2, pp. 51–60.

Sviridova, A., Stokhuijzen, D. and Verlinden, J. (2022b), "Embrace the Change: Framing Demonstrators as an Alternative to the Mass Production Norm in Industrial Design Education", *[ ] With Design: Reinventing Design Modes*, Springer Nature Singapore, Singapore, pp. 601–613.

Tharchen, T., Garud, R. and Henn, R.L. (2020), "Design as an interactive boundary object", *Journal of Organization Design*, Springer Science and Business Media B.V., Vol. 9 No. 1, pp. 1–34.

Triantafylli, N. and Bofylatos, S. (2019), "'Poke it with a stick', using autoethnography in research through design", *Conference Proceedings of International Conference 2019 of the DRS Special Interest Group on Experiential Knowledge*, pp. 87–102.

Unfold Design Studio. (2010), "l'Artisan Électronique", available at: http://unfold.be/pages/l-artisan-electronique.html (accessed 26 January 2023).

University of Stuttgart. (2021), "Demonstrator | CRC1244 | University of Stuttgart", available at: https://www.sfb1244.uni-stuttgart.de/en/demonstrator/ (accessed 26 January 2023).

Verlinden, J. (Jouke C. (2014), *Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews*, Technische Universiteit (Delft).

Aleksandra Sviridova

Aleksandra Sviridova has an extensive track record and network in the field of digital design, 3D printing, and prototyping. In her working life of more than 5 years of industry, her interest in the overlap between the arts and technology grew, as well as a passion to learn more, after which she followed the training for integrated design with summa cum laude in Dessau. She is currently pursuing her PhD at the Antwerp Design Factory, part of the research group of Product Development, University of Antwerp. Promotor is Prof. Jouke Verlinden.

Jouke Verlinden

Prof. Dr. Jouke Verlinden is the spokesperson of the research group of product development at the Faculty of Design Sciences. His research focuses on Augmented Fabrication: cyber-physical manufacturing and mixed reality and digital fabrication for improving (augmenting) human-centred design. He has published >120 scientific articles and several patents. He is editor-in-chief of the Journal of Design Research (JDR). Furthermore, he acted as guest editor for CAD journal, International Journal of Interactive Design, Engineering, and Manufacturing, International Journal on Automation Technology, while he co-founded a magazine series on Augmented Reality and Art. Recently, one of his co-authored works received the European Heritage Award for the Scanning for Syria project (2020), the best paper award at the ASME DETC conference (2017), while he received the 2016 Purmundus Award for the 3D printed bicycle.

Review Team

Bilge Merve Aktaş, Independent Researcher, USA
Camilo Ayala-Garcia, Free University of Bozen-Bolzano, Italy
Jocelyn Bailey, University of the Arts London, United Kingdom
Anne Louise, Bang, VIA University College, Denmark
Massimo, Bianchini, Politecnico di Milano, Italy
Thea Blackler, Queensland University of Technology, Australia
Monica Bordegoni, Politecnico di Milano, Italy
Marco Bozzola, Politecnico di Torino, Italy
Ingrid Calvo Ivanovic, Universidad de Chile, Chile
Marina Carulli, Politecnico di Milano, Italy
Daria Casciani, Politecnico di Milano, Italy
Mauro Attilio Ceconello, Politecnico di Milano, Italy
Manuela Celi, Politecnico di Milano, Italy
Shujoy Chakraborty, University of Madeira, Portugal
Erminia D'Itria, Politecnico di Milano, Italy
Doriana Dal Palù, Politecnico di Torino, Italy
Caterina Dastoli, Politecnico di Milano, Italy
Delia Dumitrescu, University of Borås, Sweden
Chele Esteve Sendra, Universitat Politècnica de Valéncia, Spain
Mark Evans, Loughborough University, United Kingdom
Venere Ferraro, Politecnico di Milano, Italy
Camilla Groth, University of South-Eastern Norway, Norway
Francesco E. Guida, Politecnico di Milano, Italy
Lars Hallnäs, University of Borås, Sweden
Tincuta Heinzel, Loughborough University, United Kingdom
Ruben Jacob-Dazarola, Universidad de Chile, Chile
Frances Joseph, Auckland University of Technology, New Zealand
Francesco Leoni, Politecnico di Milano, Italy
Dirk Loyens, ESMAD - School of Media Arts and Design, Portugal
Angella Mary Mackey, Amsterdam University of Applied Sciences, Netherlands
Maarit Mäkelä, Aalto University, Finland
Ilaria Mariani, Politecnico di Milano, Italy
Francesca Mattioli, Politecnico di Milano, Italy
Alvise Mattozzi, Politecnico di Torino, Italy
Michele Melazzini, Politecnico di Milano, Italy
Giuseppe Mincolelli, Università di Ferrara, Italy
Martina Motta, Politecnico di Milano, Italy
Troy Nachtigall, Amsterdam University of Applied Science, Netherlands
Ki-Young Nam, KAIST, South Korea
Nithikul Nimkulrat, OCAD University, Canada
Kenta Ono, Chiba University, Japan

Francesca Ostuzzi, Universiteit Gent, Belgium
Stefano Parisi, Industrial Design Engineering, Netherlands
Bruno Leonardo A. Perelli Soto, Universidad de Chile, Chile
Gabriele Pontillo, Università degli Studi di Firenze, Italy
Vesna Popovic, Queensland University of Technology, Australia
James Christopher Postell, Politecnico di Milano, Italy
Patrick Pradel, Loughborough University, United Kingdom
Lucia Rampino, Politecnico di Milano, Italy
Louise Ravnløkke, Design School Kolding, Denmark
Angari Roberta, Università della Campania "L.Vanvitelli", Italy
Alessia Romani, Politecnico di Milano, Italy
Maximiliano Ernesto Romero, Università Iuav di Venezia, Italy
Chiara Scarpitti, Università della Campania "L.Vanvitelli", Italy
Daniela Selloni, Politecnico di Milano, Italy
Carlo Emilio Standoli, Politecnico di Milano, Italy
Mila Stepanovic, Independent Researcher, Italy
Livia Tenuta, Politecnico di Milano, Italy
Susanna Testa, Politecnico di Milano, Italy
Secil Ugur Yavuz, Free University of Bozen-Bolzano, Italy
Julia Valle-Noronha, Aalto University, Finland
Fabrizio Valpreda, Politecnico di Torino, Italy
Aart van Bezooijen, Free University of Bozen-Bolzano, Italy
Andrea Wechsler Pizarro, Universidad de Chile, Chile

Eksig 2023

"From Abstractness to Concreteness – experiential knowledge and the role of prototypes in design research"

MILANO

19.06 — 20.06

2023 eksig
DRS special interest group on experiential knowledge

Design Research Society DRS

POLITECNICO MILANO 1863
DIPARTIMENTO DI DESIGN