Prototyping and Experiential Knowledge

UNFOLDING SHIFTING VIEWS ON THE USE OF PROTOTYPES IN DESIGN RESEARCH

Edited by
Nithikul Nimkulrat, Silvia D. Ferraris, and Francesca Mattioli

FrancoAngeli
DESIGN INTERNATIONAL

Design International series

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Foreword

Pieter Jan Stappers

Prototypes and prototyping: the noun and the verb

Prototypes – the things we make in order to find out things – have gained increasing attention in the design research community. The term “prototype” had been around for a time: in industry, it refers to “the last tryout before going into production”, in psychology to “an instance of a set that is the most recognizable example”. But in the past few decades, the term has become a major instrument in bringing about experiential knowledge. This book is exemplary of that grown interest, and its parts *envisioning*, *exploring*, *comprehending*, and *developing* sum up well the main purposes for which prototyping is done.

Nouns and verbs

The title of this collection aptly carries both the noun *prototype* and the verb *prototyping*. Their contrast – noun and verb – reflects some tensions in academic research. We (i.e., people: researchers, me, you, all people) think differently when we use a noun or a verb. It's not how the terms are defined in the dictionary, but what they evoke in us. Nouns refer to objects, verbs to processes, and we are geared to think differently with each. From our childhood experiences in stacking cubes.

We can easily think of nouns/objects as existing by themselves, existing in multiple copies that we can compare one to the other and conclude they are the same, we can store them somewhere and find them back unchanged. One cube is much like the next.

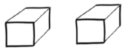
But verbs/processes are different. Processes unfold dynamically. Each time you stack one cube atop another, you do it a bit differently than before – sometimes quicker, sometimes more aligned or a bit off, sometimes with a pause in your motion. When you've done it, the action is gone.

This affects how we think with nouns and verbs. When described as a noun, something seems objective, repeatable, simplified. Described as a verb, we are provoked to think of who did the action, in what situation, with what qualities. We realize that each time is different, and that how it takes place depends on many factors.

Nouns and verbs have different ways of structuring, as can be seen in a thesaurus: Nouns are grouped in tree-like hierarchies – *a mouse is a mammal is an animal is a living thing and so on*. Verbs are less organized, a few dozen clusters, but little hierarchy.

Academic training tends to favour nouns, probably due to their structure of comparing and ordering. Academics seem to be trained to turn everything into a noun (including turning verb forms into infinitives), but this makes it easy to overlook the things verbs are good for: evoking context, signifying variations and modulations in execution. The term *zombie words* was introduced to describe the way descriptions seem to "lose life" and make us forget the nuances and richness of experience that is a part of knowledge. That is illustrated by the way some speakers, when asked to give an example of an abstract term, reply not with an example of something you could meet in the world, but just another term at one layer of abstraction below it. Within the logic of the noun-tree, that may make sense; within the logic of the provoking-verb, it misses the point.

Table 1.
Comparing the meanings of nouns and verbs.

nouns	verbs
“prototypes”	“prototyping”
all are the same 	individuals 
objects	performing actions
static	unfolding
timeless	each time different
detached	situated: evokes actor, setting, goal…
comparable	modulated
ownable	fleeting, evaporating

Prototype – the noun

The prototype as a noun/object is well established (we often think of a material form, but also a song and a dance have their developments with prototypes, as do services and performances). Prototypes as objects have been used for different purposes: as a proof of concept (demonstrator), as a speculative provocation (vision statement), as an instrument for intervention, observation, or measurement, as a carrier of knowledge, maybe a boundary object. One distinction I found helpful is Löwgren’s notion of an area of *middle level knowledge* standing inbetween the two extremes: *general theory* and *particular artefacts*.

Table 2.
Different knowledge functions as *middle-level knowledge*.

general theory
guidelines
patterns
prototypes
heuristics
…
particular artefacts

The distinctions between theory and particulars are familiar, but the level inbetween, where the richness of experience is coupled to (some) abstractions from theory, is where prototypes thrive. Together with other tools like guidelines, patterns, recipes, they occupy this *middle-level knowledge*, bridging between the stuff of experience and the abstractions of high theory.

Prototyping – the verb

When it comes to the verb, the process, there is another challenge, again one of telling the rich story without losing our audience in complexity. That is the story of iteration. In design, and other areas, the story of what we did follows a linear, seemingly causal, structure. Take a standard narrative of a design process: exploring criteria leads to generating ideas, leads to synthesizing this into a "concept product" leads to iteration of a few "prototypes" leads to the final product. That's how we tell the story. This standard structure helps the reader find their way but is easily taken as a singular logical sequence of events.

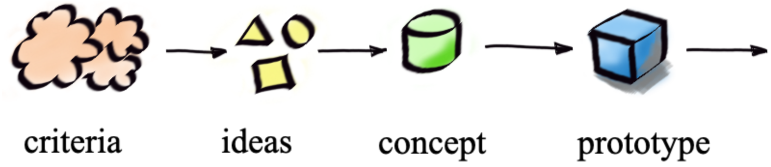


Figure 1.
Storyline sequence.

In reality, the process was much messier – especially in explorative research, or new product development, ideas come up all over the place, new criteria are discovered during prototyping, and old ideas are being pulled back into play as new opportunities and constraints take shape. The story is much more complex, as shown in the picture below. Here the horizontal steps have transformed into *swimlanes*, with a general time development from left to right and from bottom to top. Yet within this landscape many jumps back and forward as new connections are made, as new combinations occur, and new possibilities and criteria emerge. Sure, prototypes are constructed on the basis of ideas, but these ideas get changed on the basis of considerations that emerge in making the prototypes, observations from testing them, and various discussions and reflections along these activities.

Yet the storyline format requires a simple logical sequence of events, constructed in hindsight. This of course helps the audience at any point to know where they are in the landscape of activities. But it hides much of what happens during the process, and the knowledge that was generated and is not communicated. In part it stays with those who did the prototyping, remembering discarded trials which later bring them inspiration when facing a new challenge. In part it evaporates.

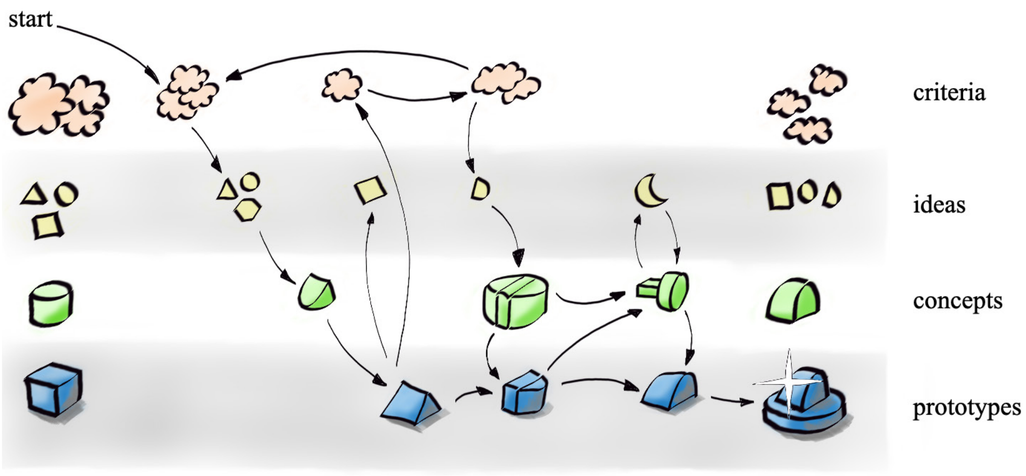


Figure 2. Prototyping history unfolding over swimlanes.

Over the past two or three decades, design research has come a good way. The EKSIG conference series has played a vital role in this progress, connecting the grounded richness of experience 'in the mud' and general theory "in the sky" in that space inbetween where most of human life takes place.

Notes

Note 1
Some of my understanding about prototypes can be found more academically described in Stappers, P. J., & Giaccardi, E. (2017). Research through Design. In M. Soegaard, & R. Friis-Dam (Eds.), *The Encyclopedia of Human-Computer Interaction*. The Interaction Design Foundation.

Note 2
For Löwgren's midlevel knowledge, see Höök, K., & Löwgren, J. (2012). Strong concepts: Intermediate-level knowledge in interaction design research. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 19(3), 23.

Note 3
The evocative word "zombie nouns" was introduced by Helen Sword; I learned about it in Pinker, S. (2014) *The Sense of Style*. Allen Lane.

Transitioning from abstractness to concreteness through prototyping

Silvia D. Ferraris, Nithikul Nimkulrat

Introduction

The content of this book represents the third step in developing an investigation into the role of prototypes in design research.

The first step was the research project, PARIDE (Prototipi Avanzati per la RIcerca di DEsign, Advanced Prototypes for Design Research), developed by a team of researchers at the Department of Design at Politecnico di Milano in 2019–2021. The research was based on the literature review, a collection of case studies, and a conversation with experts. From these phases, the research team outlined the findings. On the one hand, the theoretical framework and established criteria offer a structured understanding of the roles that prototypes play within design research. On the other hand, the study presents a broader perspective on the phenomenon, uncovering new insights and directions that may inform and advance future research in the field (Ferraris, 2023a).

Afterward, the authors organized an international conference on the same topic to widen the range of examples of the role of prototypes in design research today and to develop the topic further. Thus, the second step of the investigation was the conference "From Abstractness to Concreteness – Experiential Knowledge and the Role of Prototypes in Design Research" hosted by the Department of Design, Politecnico di Milano, Italy, in June 2023. The conference was one of the biennial International Conferences of the Design Research Society (DRS) Special Interest Group on Experiential Knowledge (EKSIG). After a peer-review process, the conference committee selected 55 papers representing a broad perspective on the research areas and practices of design where prototypes play a role. The papers were collected and published as conference proceedings.

As a third step, reading the papers through the lens of the research findings in the first cycle (Ferraris, 2023a) led us to the compilation of this book. We invited eleven conference participants and one keynote speaker to write a chapter updating their research or proposing a new example of their use of prototypes in their work. Throughout this collection, we find confirmation of the theoretical framework and elaborate on some open questions from the PARIDE research project in the first cycle that let us express extra reflections on the role of prototypes in design research today as enablers of creativity and experiential knowledge.

The PARIDE research project

PARIDE investigated the role of prototypes in today's design research (Ferraris, 2023a). As a premise, the research team considered two correlated phenomena explaining the evolution that such a role appeared to have: on the one side, the technological evolution that enables and requires making new types of advanced prototypes, and on the other side, the progress of design as an academic discipline which continuously widens its perspectives, fields, and research methods and – thus – the uses it makes of prototypes (Erlhoff & Marshall, 2008; Koskinen *et al.*, 2011, Chapter 8; Stappers *et al.*, 2014).

At first, the team set up the research area starting from the specific discipline of *product design* and subsequently extending it to adjacent domains, including material design, interaction design, and related fields such as engineering and computer science – disciplines that collaboratively contribute to the development of advanced products (Barati *et al*., 2017; Gill, 2013; Hallgrimsson, 2012; Houde & Hill, 1997, Chapter 7; Moultrie, 2015; Niedderer, 2013; Pei *et al*., 2011; Sanders, 2013). During the literature review, the team included more design fields, such as service design, participatory design, critical design, and design fiction, to comprehensively understand the phenomenon. The findings can be summarized as follows.

Definition of prototype

The first aim of reading the literature review was to choose one definition of the prototype that would direct the study. To this end, the team systematically gathered publications referencing prototypes and related terminology (e.g., models, probes, artefacts), intending to construct a comprehensive understanding of the concept (Houkes & Vermas, 2010, Chapter 7; Koskinen *et al*., 2011, Chapter 8; Gaver *et al*., 1999; Nimkulrat, 2009). However, this process revealed two key observations:

1. The term prototype assumes different meanings in different disciplinary contexts.
2. Analogue words, such as models, artefacts, and many others, have the same meaning as prototypes in different contexts.

Consequently, the team concluded that seeking a universal definition applicable across all disciplines was unproductive. Instead, a definition suited to the design field was proposed: “In design, prototypes are *intentional* and *transient* objects made to concretize a conceptual idea” (Ferraris, 2023b, p. 136).

Theoretical framework

The research examined the traditional and emerging roles that prototypes play in various fields of design research in both academic and professional contexts. Ultimately, the team developed four theoretical concepts that describe the phenomenon.

1. The general role of prototypes in design research is to support the transition from abstract concepts to defined design solutions – from abstractness to concreteness.

2. Prototypes can support the generation of new knowledge, *about* and *beyond* the prototype itself, that can be translated into theoretical findings.
3. The role of the prototype evolves with the context in which it is applied, in particular, the availability and integration of advanced technologies and the development of the design discipline and its broadening and finalizing fields of research, approaches, and tools.
4. Prototypes can support such a transition in any design process, from purely speculative to practice-oriented studies. The context in which the research takes place frames the role of the prototype more than other criteria.

Indeed, one of the most important findings is the six essential criteria – *aims*, *discipline*, *terminology*, *context*, *fidelity*, and *process phase* – that frame the role of all prototypes in any design research (Barzilai & Ferraris, 2023, p. 15). Among these criteria, the *aims*, the *context*, and the *process phase* are the most relevant. Indeed, prototypes as "intentional and transient objects" are created for a specific scope – aim – in the research context so that they might even be discharged once the scope is reached. Hence, their existence and characteristics derive from the research's general scope and the specific phase of the process in which they apply. For instance, draft simple models could be used in the first exploratory part of the design research to share provisional ideas among a team of designers. In speculative design research, the models could represent abstract, conceptual ideas (i.e., storyboards showing the story of how to use a service in 20 years); in practice-based research, they could be more concrete concepts (i.e., clay matches for a new ergonomic toothbrush). Throughout the research process, the team systematically extracted and analysed the stated aims from each reference and case study, subsequently organizing them into nine recurring categories of aims: *develop*, *assess*, *communicate*, *comprehend*, *investigate*, *explore*, *provoke*, and *envision* (Barzilai & Ferraris, 2023, p. 16). When arranged sequentially, these categories reflect the progression of the design development process. Each prototype is, therefore, created to fulfil a specific purpose corresponding to distinct phases within the broader context of design research. The first part refers to the traditional role prototypes played in the industrial manufacturing process – that of being "the first type of a mass-produced product" to develop, assess, and communicate the new product. While the other aims referred to using prototypes in research to identify problems, investigate issues, instigate debates, anticipate visions, and produce knowledge, enabling the translation of concepts from abstract to concrete.

The international conference

The conference "From Abstractness to Concreteness – Experiential Knowledge and the Role of Prototypes in Design Research" was then organized in 2023, proposing the topic:

> **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. […] The conference aims at eliciting a conversation around the current and multiform panorama of experimentations around and with prototypes. (Ferraris *et al.*, 2023)**

The call did not propose predefined tracks. On the contrary, the committee clustered the papers using a bottom-up process and eventually formed eight groups by topics that appear to be related to the disciplinary context/content of the research:

1. Interaction, data and AI (9 papers)
2. Materials and digital (5 papers)
3. Materials and crafts (5 papers)
4. Sustainable and biological solutions (5 papers)
5. Mobility and transportation (4 papers)
6. Service design and policymaking (5 papers)

7. Society and health (4 papers)
8. Fiction and speculative design (5 papers)

These tracks represent the design areas where researchers are exploring the use of prototypes. They range from tangible types (e.g., material and crafts, biological solutions, etc.) to intangible design realms such as speculative design. They also show that design research encompasses transdisciplinary topics, including other areas (e.g., data and AI, transportation, policymaking, etc.).

In addition to the eight disciplinary tracks, the papers that reflected on the role of prototypes, focusing on the process and methods for design research and education, were grouped into the following two tracks:

1. Research processes and methods (8 papers)
2. Education processes and methods (5 papers)

So, upon analysing the collection of papers, it appeared that the research context is a trait that allows them to group clearly. Nevertheless, when we observed the papers' contents more closely, we noticed the presence of the criteria (especially the aims) and other matters that stimulated us to discuss the role of prototypes in design research through other perspectives.

Further reflections on the role of prototypes as enablers of creativity and experiential knowledge

Regrouping by aim of prototypes

Although the papers presented at the conference revealed the use of prototypes in various kinds of design research, all somehow highlighted that prototypes help step forward in the research process by achieving some scope. Thus, we revisited the nine main types of aims – *develop*, *assess*, *communicate*, *comprehend*, *investigate*, *explore*, *provoke*, and *envision* – and, upon mapping them against the papers to see which aims encompassed more cases, we discovered that the following four aims were prominent:

1. *Envisioning* refers to any step of the design research process where prototypes facilitate the representation and construc-

tion of new visions. It is often a scope of the early steps of the research, but it could be the final aim (i.e., to design a future scenario).
2. *Exploring* refers to all cases in which prototypes enable not only material and tangible experimentations, but also conceptual and speculative ones.
3. *Comprehending* highlights that prototyping enables design researchers to observe and decipher their matter so that they eventually understand unknown aspects of their doing.
4. *Developing the design process itself*. In research about design practice, design researchers can test their theories, methods, and processes by prototyping.

Based on these four aims, we, therefore, selected and invited the authors who could help us highlight what scopes can be achieved through prototyping (see Section 5, where we summarize the chapters).

Emerging topics about the role of prototyping in design research

From the PARIDE research project, several topics and extra considerations have emerged for further discussions. We aim to address them through the chapters included in this book.

The nature of the transition

One topic is about the nature of the transition from abstractness to concreteness. Should it always be achieved through tangible matter?

We learned that this consideration depends on the design area of the research. Those who work in any area close to product design or product interaction, where material and technological aspects are prominent, tend to imply the making of physical objects and the use of physical prototypes. However, what is interesting is that the materiality of models and probes also has value for developing an understanding of theoretical concepts (see Chapters 4, 8, and 9).

Possibly, the answer to this question is that the tangible nature of the prototype depends on the nature of the research and the aim it targets.

Visual representation tools

Another topic of discussion is visual representation tools. Are they prototypes or not?

Several authors argue or suggest that representational tools constitute a distinct category of objects separate from prototypes (Hallgrimsson, 2012; Lim *et al*., 2008; Pei *et al*., 2011; Yang, 2005). However, tools such as storyboards, flowcharts, user journeys, task analyses, mood boards, and other visual artefacts are often employed to develop, communicate, anticipate, evaluate, investigate, and shape concepts related to tangible products, interactions, and user experiences. From this perspective, such visual artefacts contribute to the full spectrum of research activities in much the same way as prototypes. Consequently, when considering their functions and purposes within the design process, visual tools can be seen as fulfilling roles equivalent to those of prototypes. Thus, integrating these two categories – visual tools and prototypes – appears both reasonable and conceptually coherent.

Moreover, we observe the application of virtual experiences (Stjepanovič 2017; Volino *et al*., 2015) to support designers in the development process or to show clients the product. In contemporary design practice, numerous digital artefacts – such as renderings, photomontages, and videos – are increasingly used in place of physical prototypes to enable users to engage with new solutions within fully immersive virtual environments. This shift suggests that the distinction between visual and tangible prototypes may be less significant than previously assumed. Instead, categorizing prototypes based on their interactivity (passive vs. interactive) and ontological status (real vs. virtual) appears to offer a more meaningful framework for analysis (Ferraris, 2023a) (see Chapters 5, 7, and 11).

Fidelity

The next topic of discussion is the concept of fidelity. Should we use it or not?

When reading the literature, several authors bring up *fidelity* when describing prototypes (Hallgrimsson 2012; Lim *et al.* 2008; McElroy 2016). Fidelity refers to the degree of similarity between a prototype and the final product. While it is commonly associated with the visual and tactile qualities – the “look and feel” – it may also encompass functional, performance-related, and interactive attributes. Fidelity is typically described along a continuum from low to high, indicating the extent to which a prototype approximates the final design. This scale ranges from rudimentary mock-ups to sophisticated, fully functional prototypes. Moreover, the level of fidelity is often aligned with specific phases of the design process, reflecting the evolving requirements and objectives at each stage (Ferraris, 2023a).

Through the discussion with experts, we agreed that the best way to use the fidelity concept is to associate it with the aims of the prototype in the design process. So, the level of fidelity is determined based on its appropriateness for the research step and the intention of the prototype (see Chapters 2 & 3).

Also, we understood that the stakeholders involved in the process should be educated about fidelity. When the prototypes seem real, the clients might think that the final product is feasible and almost ready. So, to avoid misunderstandings and false expectations, educating the audience is important.

Finished products

An important consideration emerging from the research concerns the point at which a prototype transitions into a finished product.

As observed, particularly within the context of speculative design, a prototype – originally conceived as part of a design research process – may concurrently be regarded as a final artefact. For instance, a prosthetic prototype may be reinterpreted as a work of art, thereby acquiring the status of a finished object within a different disciplinary or cultural context (Ferraris, 2023b, p. 134). This phenomenon is especially evident in instances where the boundaries of design intersect with those of art or technology, further supporting the characterization of prototypes as transient objects that are subject to continual evolution.

Nonetheless, the potential for a prototype to become a finished product may not be as important as them being intentional objects. Within design research, prototypes are created with a specific purpose – most notably, to communicate the envisioned future of a project. They serve as tangible manifestations of conceptual ideas, crafted to engage stakeholders and audiences by making abstract futures more accessible and comprehensible (Ferraris, 2023a) (see Chapters 1, 6, and 10).

The structure of the book

The book is structured into four parts – *Envisioning through Prototypes*, *Exploring through Prototypes*, *Comprehending through Prototypes*, and *Developing the Design Process through Prototyping* – each consisting of three chapters.

The first part, *Envisioning through Prototypes*, focuses on the role of the prototype in representing and constructing new visions at various stages of the design research process, whether in the early or final steps. The first chapter in this part is "Beyond Prototyping: Demonstrators, Provotypes, and the Narrative Turn in Design Research" by Aleksandra Sviridova and Jouke Verlinden. Typically considered near-finished commercial products in the field of industrial design created for evaluating designs, demonstrators in this chapter are instead explored in line with associative, speculative, and critical design to envision the future. While high fidelity is no longer the essence of demonstrators here, how the object is designed depends on how abstract or concrete the envisioned future is. The focus shifts to audience engagement and how to communicate to various stakeholders the discovered problems and visions of potential solutions.

In contrast, low-fidelity prototyping is the primary focus of Rolf Brändle and Paula L. Schuster's chapter "Deliberately Abstract: The Tactics of Low-Fidelity Prototyping". The chapter examines the approach of designing intentionally simpler models for various purposes and explores their potential for knowledge production in transdisciplinary research. The authors highlight several tactics of low-fidelity prototyping and emphasize the importance of prototyping literacy, which is about choosing the appropriate level of fidelity to suit the purpose of the prototype and critically reflecting on the prototyping process.

Low-fidelity prototyping is also examined by Francesca Mattioli and Martina Labarta Labrador in Chapter 3, "Prototyping

Collaboration: Managing Collaborative Projects in Design Education", but in the context of collaborative learning in design education. The authors look at the role of a low-fidelity prototype of a management platform in supporting student teams to understand the multifaceted aspects of their collaborative work and to envision strategies to promote not only the team's effectiveness but also their members' well-being.

Exploring through Prototypes, Part II of the book, emphasizes the inherent capacity of prototypes and prototyping to enable experimentation that can lead to a better understanding of theoretical concepts. Experimentation here is not limited to tangible prototypes but extends to conceptual and speculative ones as well. This part opens with Gemma Potter's chapter entitled "Graft-Games: Investigative Prototypes for the Cumulative Exploration of Similarities between Craft and the Play of Videogames". In this chapter, theoretical crossovers between craft and gaming are explored through an experimental prototyping approach called "grafting" and the resulting "grafted" prototypes. These prototypes enable members of the public to engage directly with interactions between digital games and craft elements, helping to identify theoretical crossovers between the two fields that would not have been possible otherwise.

Experimentation with tangible and digital materials through prototyping is evident in Chapter 5, "Experiential Substance: Tactile Translations Using Digital Materials", by Elizabeth Meiklejohn, Felicita Devlin, Caroline Silverman, and Joy Ko. With an emphasis on engaging multisensory interactions with materials, the authors explore methods of designing textiles with specific sensory qualities through physical and digital prototyping. Starting from an initial physical prototype (or a "generalized swatch", in textile terminology) that highlights precise multisensory descriptions, rendering software is used to envision a prolific array of forms and tactile qualities for novel, sensorially rich textiles. Such methods extend the capacity of a textile swatch, which used to represent a single design.

In "Slow Prototyping in Biodesign: Designing with the Living in Hybrid Laboratories", the final chapter of this part, Francesco Cianfano, Tommaso Celli, Marco Marseglia, and Valentina Rognoli discuss DIY experimental approaches to designing biomaterials. Such exploration through prototyping living organisms, which grow, respond to stimuli, and exhibit agency – makes biomaterial prototypes dynamic, unstable, and transformative systems. This leads the authors to propose the notion of *slow prototyping* – a design practice in hybrid spaces between science and design, and care and learning, that requires non-linear iterations and openness to uncertainty.

Part III, *Comprehending through Prototypes*, highlights how prototyping enables design researchers to observe, make sense of, and eventually understand the unknown aspects of their design inquiries. The first chapter in this part is Ayşe Özge Ağça and Jacob Buur's "Turning Abstract Data Concrete: Drawing and Tinkering with Data". The chapter examines how to engage young people experientially in understanding their own data through the acts of data drawing and prototyping. Through a case study of design students tracking their water consumption and waste recycling, the chapter argues that drawing and prototyping make abstract, hidden data comprehensible and suggests their potential to change consumption habits.

In Chapter 8, "Hands-on Thinking: Prototyping as a Pathway to Theoretical Understanding", Sisse Schaldemose examines how students' understanding of theory in higher education can be enhanced through prototyping with tangible materials, illuminating the support that prototyping offers in transitioning from abstract ideas to concrete reflection and practice. The author points out that physical prototypes of a theory can encourage students' more nuanced engagement and collective exploration of what is fundamental in the theory.

This part closes with Rose Dumesny and Dorian Reunkrilerk's chapter entitled "Prototyping-as-debate: exploring the situated nature of politics in design". In this chapter, the authors examine prototyping as a political experience in design practice and attempt to outline the conditions that contribute to it. Through design cases analysed using sociology and political science literature, the authors illuminate ways in which designers can potentially embed political dimensions in their practice and propose a co-design framework for bringing together human and non-human actors in design debates.

The fourth and final part of the book, *Developing the Design Process through Prototyping*, returns to the original function of prototyping in design practice, focusing on the development of the design process itself. When design researchers test their theories, methods, and processes through prototyping within design research contexts, they simultaneously develop processes applicable to their professional practice.

This part opens with "Rethinking Assistive Technologies through Hybrid Manufacturing: A Case Study on Designing for Amyotrophic Lateral Sclerosis (ALS)", a chapter by Yash Bohre, Purba Joshi, and Rowan Page. In this chapter, the authors attempt to fill a gap in accessibility caused by a one-size-fits-all approach optimized for mass manufacturing in assistive technologies (ATs). They point out that such an approach fails to address the evolving and highly specific needs of individuals with progressive conditions like MND or ALS. Their research applies hybrid manufacturing, combining 3D printing and handcrafting, to develop a custom assistive device, leading to a proposal for a flexible prototyping approach and design process that offers more personalized and responsive AT solutions.

The next chapter in Part IV is "A Virtual Reality Experiential Prototyping Tool for the Application of Anthropometry in Complex, Confined Human Environments", by Peter Schumacher, Francois Fraysse, Brandon Matthews, Simon Modra, Dominic Thewlis, Geoff Langridge, and Jack Beven. It presents a more effective way to prototype with digital human manikins (DHMs), offered by the real anthropometric experience system (RAES), which employs a DHM poser and a virtual reality (VR) environment as tools for applying anthropometry in designing complex, confined human environments.

The book – and Part IV – closes with Aldo Sollazzo's chapter, "Urban vision: AI-driven spatial analytics for walkability in Barcelona's superblocks," which describes an example of experimentation and prototyping of the most advanced technologies (in this case, AI-based) for a large-scale project, such as urban spaces. The research introduces a design method that functions as a descriptive model and a systematic, knowledge-generating framework by integrating static and dynamic data through a prototype-driven analytical process supported by computational tools.

New insights

Several new insights surface across the chapters included in this anthology.

We reckon that prototypes produced within design research – where the designer is also the researcher – unlock creativity (Rosenman & Gero, 1993) and, in return, benefit the researcher's design practice through the development of their design process. This is evident in Chapter 5, where both physical and digital prototyping generate novel textile designs with defined sensory qualities, without the necessity of creating multiple swatches (i.e., physical prototypes).

Indeed, to facilitate the creative process, design researchers use prototyping in a serendipitous approach to research that welcomes non-linear passages and uncertainty. Such openness boosts creative processes in all fields. Possibly, we argue, that is exactly the role of design researchers in multidisciplinary and transdisciplinary research. Many chapters present research fields that include other disciplines, for instance the convergence of design and political-social matters in Chapter 9, the merging of craft and gaming in Chapter 4, the use of design in pedagogical context of social work education in Chapter 8, and the use of flexible prototyping to develop medical devices in Chapter 10. It looks like the designers' ability to explore and envision through prototyping is the added value given by design in a multidisciplinary and transdisciplinary context.

Furthermore, when prototyping is intentionally used in design research as a research method, and a rationale for its use is provided, it can make the experiences of research participants explicit, concrete, and engageable. This is demonstrated in Chapter 7, where drawing and prototyping enable participating students to engage with their own data. Similarly, in Chapter 8, the author remarks that prototypes – here intentionally defined as opposite to visual models – can be "shared objects of thought", enabling collective exploration and inviting students into a more nuanced engagement with theory. With this in mind, we argue that in the world that is becoming more and more digital, we, design educators, will have to make an extra effort to ensure that some of our students' learning experience goes through a physical experience. Otherwise, they will lose the chance of exploring and learning through openness to uncertainty and unforeseen discoveries.

The more traditional role of prototypes was to facilitate the progress in the making of new products through the product development process. This role still exists, and an intense effort is made by design researchers and practitioners to improve prototypes and prototyping to enhance, shorten, and/or optimize the design process. Chapters 10, 11, and 12 show how hybrid manufacturing, virtual reality, and generative artificial intelligence can today improve designers' work.

The prototyping process embodies the experiential knowledge (Stappers, 2014) of the designer and/or design team. This is particularly apparent in Chapter 6, when prototyping biomaterials using living organisms that slowly but continuously transform, the designer-researchers are actively involved not only in material tinkering but also in observing these transformations. What happens during this slow prototyping process is considered experiential knowledge that may not be generated without the act of prototyping. It is up to designer-researchers to transform such knowledge into theoretical findings that can inform and better the design processes and consequently the research results.

Looking at the role of prototyping in design research, it supports the generation of both experiential and theoretical knowledge. It promotes the collaboration of designer-researchers with stakeholders from any other disciplines as long as design facilitates the passage from abstractness to concreteness. The passage is supported by physical, digital, and/or virtual prototypes that enable exploring and envisioning research phases. Ultimately, they promote understanding and, consequently, generate new knowledge. The intensity and nature of the prototype used in a research project depend on the research questions and context. From the chapters in this anthology, not only do we notice the most relevant aspects framing the role of prototypes in design research, but we also recognize that the design discipline keeps evolving in two ways, from the very first premises in the PARIDE research. First, design increasingly includes and experiments with technologies regardless of areas of design practice and research. Second, design expands to collaborating with other disciplines to tackle new challenges, such as those opening to more-than-human design issues.

To conclude, we believe that this three-step research into the role of prototypes in design research shows an evolving picture of the phenomenon. Possibly, the collection and reading of case studies should continue so that the understanding of it could be updated and further widened. In the past, we observed the advent of computer-assisted drawing and later additive manufacturing, while today we are witnessing the advent of AI in all forms of making and sharing of knowledge also in creative fields. Now, many researchers are studying its opportunities and applications in several design areas, but only in the future, we will be able to assess the effect of it in the design discipline and the prototyping activities. The role of prototypes in design research is mutable and intrinsically linked to stream phenomena.

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PART 1

Envisioning through prototypes

1. Beyond prototyping: demonstrators, provotypes, and the narrative turn in design research

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1.1 Introduction

Design activity is often viewed as a form of problem-solving (Cross, 2001), assuming a path that connects the "existing situation" to the "preferred future" as the end (Simon, 1969). Although Western discourse often prioritizes ideas over things (Atzmon & Boradkar, 2017), the future can only be manifested if it is first described in detail (de Jouvenel, 2012). In other words, if design is considered as an assertion about the future, then the design process is the formalized intention to make it certain; it is expected to end with a concrete solution. In industrial design and product development, the intermediate steps of the design process are mostly physical: sketches, foam and paper mock-ups, clay models, etc., which fidelity often correlates with how close the project is to completion.

The word "prototype" is often used to describe the abundance of design representations on a spectrum ranging from abstractness to concreteness. Literature treats it as a model that allows designers to describe, visualize, materialize, and iteratively refine concepts until the desired result is achieved (Boeijen *et al.*, 2020; King & Chang, 2016). Over time, prototypes have evolved from mere intermediate steps preceding the final product to crucial elements in every phase of the design process. Prototypes can vary in form and fidelity (Söderman, 2001), play different roles (Houde & Hill, 1997), be used as filters or manifestations of design ideas (Lim *et al.*, 2008), and pursue objectives such as exploration, validation, specification, and communication (Verlinden, 2014). They allow designers to compare alternative design directions, reveal the context of use, support thinking, serve as cognitive anchors, test behavioural hypotheses, expose modelling flaws and errors, distil key interaction parameters, and locate limits of use (McGarry, 2005). However, this very breadth of applications also introduces ambiguity.

Consider its formal definition – "the first of its kind – the first or preliminary model of something" (Sanders, 2013, p. 63) – prototypes are anything that is not the final product. However, the distinction between them is often blurry. For example, to test Aramis, a guided rapid transit project developed in France, its engineers built five full-size capsules, a movable station, a control post, and a parking lot for their automatic coupling system. Tests on a kilometre-wide track and later, at the experimental station, were successful (RATP, n.d.). The engineers were convinced that their prototype was ready for large-scale implementation (Latour, 1996). However, Aramis never entered the French transport system. If a prototype is "preliminary", when does it become "final"? Even the concreteness of this prototype is debatable: the test station only had one loop and some technical railways to store the capsules and rearrange them. At some point, the system was supposed to be implemented in a large city, such as Paris. In that sense, the trial remained an abstract approximation of the intended system.

That said, prototypes can represent any stage of the design process and can be anything from abstract sketches to fully realized artifacts. Moreover, physical prototypes can be used for projects that do not intend to result in a tangible product, acting as communication tools between team members, clients, manufacturers, and potential users. However, when shared understanding is needed among multiple stakeholders, prototypes might be ineffective. In fact, to serve as a medium, prototypes have evolved into new concepts. Technology demonstrations showcase the performance of advanced technological systems and various components to a broader audience (Sviridova & Verlinden, 2023). Provotypes (i.e., provocative prototypes) and critical artifacts are used to steer participatory discussion and exploration (Mogensen, 1992). Moonshot projects achieve radical improvements by combining technical challenges with societal relevance (Casadevall & Fang, 2016; Purmal *et al*., 2016). Finally, demonstrators focus on effective conveyance and message facilitation (Moultrie, 2015). While these notions look toward possible futures, not all of them aim to make them "preferred". For instance, provotypes and demonstrators probe how people respond "in the present" to one of the possible scenarios of "the future", while critical design uses storytelling to question what "preferred" even means.

In this chapter, we will explore the difference between these concepts from the perspective of representing the future and highlight how they manifest it through methods of storytelling.

1.2 Envisioning the future

One way to describe a preferred future is to bring novel ideas into the material world. The path to it is divided into several stages that academia sees as the difference between basic and applied research. The commonly used science, technology, application, market (STAM) model explores how ideas mature, highlighting that their audiences and contexts widen progressively (Phaal *et al*., 2011). Industry recognizes this progression as the technology readiness level (TRL) framework, developed by the National Aeronautics and Space Administration (NASA) to assess the "maturity" of technologies (Mankins, 1995).

However, for projects aiming to influence society, focusing on just a few is insufficient. Instead, they want to develop a vision that goes beyond applied science to basic science. For example, "moonshot" refers to ambitious, groundbreaking projects that aim to make significant advancements, often without the assurance of immediate success. Such programs combine both perspectives to tackle problems at every level, from laboratory to market, intending to influence large numbers of people. Originally inspired by NASA's Apollo program, the notion refers to a bold goal or project that pushes the boundaries of what is considered possible. In a business context, it represents a commitment to transformative innovation, often involving high risk and high reward (Purmal *et al*., 2016). Although moonshots imply planning from an abstract idea to a concrete result, they do not necessarily result in one material product. For example, the national cancer program in the USA focuses on accelerating research but also provides treatment services and educational materials to patients (Casadevall & Fang, 2016; Croyle *et al*., 2019).

On the other hand, industrial design and product development have long connected academia with the market. From the use of a novel wood-bending tool to produce over 50 million chairs (Design Museum, n.d.) to the integration of various existing technologies, such as touch-screens, into breakthrough devices (Comscore, 2009; Woggon, 2022), design has played a pivotal role in shaping technology. However, if the goal is to visualize potential future applications and convince potential funders, designing a demonstrator might be preferable.

Demonstrators, versatile concepts that combine engineering, art, and design, are currently gaining traction as an effective instrument to communicate research. They can be described as tangible artifacts that make abstract concepts visible and communicable to various stakeholders (Moultrie, 2015; Sviridova & Verlinden, 2023). In technology research, demonstrators are a common tool for introducing new technologies to the market or communicating science to the public. However, their purpose is not business-oriented: they do not sell what works, but rather what might work (Brand, 1988). In industrial design and product development, demonstrators convey an abstract message more artistically and aesthetically, while retaining their complexity. Tangible objects allow the audience to interact with them at their own pace and avoid being tied to one interpretation. Popularized by the Massachusetts Institute of Technology's (MIT) Media Lab, demonstrators are manifestations of new ways to implement innovative technology. The built artefacts show how the proposed solutions should work, allowing everyone to experience them firsthand. However, these designs are not the products themselves, but rather ways in which new technology can be utilized, while the resulting objects manifest these scenarios. For example, the digital newspaper

NewsPeek represents an answer to the question “How can digitalization or VR change media?” The design consisted of text blocks with highlighted areas that, on click, provided personalized information (Media Lab, 1986). In addition to connecting the new digital environment with familiar analogue methods, the researchers introduced the concepts of interactivity, accessibility, and information sharing. They also encouraged discussions about the economic, ethical, and philosophical issues related to free, widespread access to information.

When the discussion about possible implementation is more important than bringing the idea to market, a provotype can be used to stimulate the discussion. In system design, this concept involves challenging traditional notions of artefacts using a transcendental approach. For instance, one might consider whether a word processor should resemble a typewriter or be designed entirely differently (Ehn, 1984). The idea is to create an object that allows one to experience new practices based on current ones without focusing on how they could be improved, thereby bridging the gap between analysis and design (Mogensen, 1992). In co-design, the concept represents a robust, functioning artefact designed to challenge stakeholders’ conceptions and encourage reflection on how things could be different. It connects the practices of critical design and organizational sense-making, facilitating the transfer of user knowledge to the industry (Boer *et al.*, 2013). Existing problems become “invisible” when the tensions between such conceptions are taken for granted (Polanyi, 1958). Provotypes encourage active participation and make the problems “visible” to mediate constructive discussion.

All of these concepts transform research into products and bring them to the industry. They may seem similar, but researchers can distinguish between them based on experience. When I asked engineers from a technology research institute to define a demonstrator, they said it is “nicer and more explanatory”, “not intended to sell a final product”, or “made to express passion and show that the project was made with love”. They added that if something looks “pre-marketed”, then it should be called a prototype. Sometimes, the choice is dictated by the system. For instance, German funding only supports basic research, and the goal described in the application should be vague enough to receive funding. If the research has a potential application or context in mind, it is no longer considered fundamental, and the proposal will be rejected. This influences how precise the preferred future should be and how feasible its manifestation should appear.

In fact, demonstrators and provotypes focus more on staging possible futures than on delivering a finished solution. The concrete result becomes less important than the emotions and reactions it evokes in the audience in the present. Bradshaw (2010) emphasizes the communicative power of demonstrators in implementing research findings as innovations. Participants in his study support using objects instead of a wordy presentation: "… if a picture is worth a thousand words, then a property (here: a design or market research object) is worth a million words. Everyone benefits from seeing the models" (p. 138). According to Star and Griesemer's such artefacts can be called boundary objects, entities that are adaptable to local needs yet robust enough to maintain a common identity, enabling stakeholders with different expertise to collaborate effectively (1989). The concept of boundary objects varies greatly, ranging from material objects to words and even the Beatles (Star, 2010), meaning that on an organizational level, design can also be considered as an interactive boundary object (Tharchen *et al.*, 2020). However, while some theorists claim that boundary objects cannot be created – arguing they only *become* such once multiple groups invest them with meaning (Carlile, 2002) – others assume they can be engineered through participatory practice (Groot & Abma, 2021). We adopt the latter stance, believing that demonstrators can be designed to efficiently serve as boundary objects.

1.3 Narrating the future

Stories and narratives are one of the most common strategies for conveying a message because they enable us to condense and understand experiences in a sequence of events over time (Bordwell, 1985; Porter Abbott, 2014). They are a natural, yet inspiring and evocative way to exchange information, which is essential in design practice (Forlizzi & Ford, 2000; Lloyd, 2000). In commercial industrial design and product development, storytelling is one of the most value-adding components that increases the desirability of an object by creating an emotional engagement with the user (L. Dias & Dias, 2018; P. Dias & Cavalheiro, 2022; Glenn & Walker, 2012). However, some design practices rely on it even more.

Malpass (2017) distinguishes three categories of critical practices: associative, speculative, and critical, depending on their focus, narrative style, and how far they look into the future. Critical design uses defamiliarization to create distance between the designer and the viewer, leaving room for interpretation, with a focus on the present social, cultural, and ethical implications. Speculative design contextualizes scientific and technological trends in everyday life, exploring how innovations in industrial design and product development might influence domestic life. In contrast, associative design challenges design's norms, methods, traditions, and values. All three categories rely on design fiction, which is a blend of product design, scientific foresight, and science fiction storytelling. Design fiction materializes "what if" scenarios in tangible artefacts. An important aspect of this narrative is that satire can operate through mild humour and parody, or it can be more contemptuous and allegorical (Malpass, 2017). For example, Anthony Dunne's Faraday Chair represents the idea of having a space free of electromagnetic waves. Contrary to the current trend of escaping into the virtual world, the chair offers a physical space to take a break from today's ubiquitous technologies. To remind us of how precious such spaces may be in the future, the chair is designed so that an occupant can only fit into it by assuming a fetal position (Dunne, 1999). However, without the initial contextual narrative, the Faraday Chair looks like a simple glass cabinet.

Unlike the aforementioned critical design practices, the goal of provotypes is to guide the audience's reflection on their existing experience. As a co-creative practice, they require active participation to encourage deeper involvement in the discussion. Product concepts are used playfully to explore and expand the boundaries of a problem. In other words, the question "what if?" is supposed to be answered not by the designers but by the participants (carefully guided by the designers, though) (Brandt *et al.*, 2012). Although according to Boer and Donovan (2012), provotypes "[elaborate] on the inherent contradictions of the activity" (p. 74), their main goal is to ensure a common understanding of the problem to make possible evaluation of the proposed solution. This is reflected in the storytelling methods used in provotype design, which imply more interactivity and less satire than speculative design (To *et al*., 2022).

The design of demonstrators focuses on conveying a message to the audience. Although little is known about how storytelling is used in demonstrator design, it seems that the difference lies in how the audience receives the story. In critical design practices, the story is crafted by the designer and accompanied by an object. In prototyping design, the story is constructed through the audience's active engagement. In the case of demonstrators, the story is intrinsic to the object and can be discovered through interaction. Due to the abstractness and complexity of the matters they mean to communicate, there is often no concrete application or familiar context. Therefore, designers must first make sense of the problem themselves. Since the human brain cannot perceive abstraction without metaphors (Lakoff & Johnson, 1981), it is only natural to create a story to guide further development and help the audience comprehend it. For example, to demonstrate the benefits of an advanced optimization algorithm over the current one, the designers of the Race Track demonstrator used the metaphor of a racetrack. Two methods, represented by cars, competed in an animation projected onto a relief background representing an existing racetrack. An expert explained the details of the algorithm while the animation played (Sviridova *et al*., 2021). Even when the projection is off and no additional information is provided, the relief is still visible, so the idea of a race is still presented to the viewer.

Although design is solution-oriented and art is a form of self-expression, the ability to create objects that cause an emotional response to the auditory is where they overlap. Just like artists, designers cannot explicitly explain how they knew that the object would work the way they wanted, and in case of a lack of information, make decisions intuitively. Both often refer to their inner understanding: they knew if "it felt right" or "the outcome is not right" (Sviridova & Verlinden, 2024, p. 2450; 2025). From the positivist point of view, which is quite common in academia, it looks almost mystical. Among others, Pepper (1972) calls mystical insight negating other modes of cognition. Clarke (1973) echoes that "[a]ny sufficiently advanced technology is indistinguishable from magic" (p. 21). Demonstrators are hardly sorcery, but their power to move audiences partially emerges at the intersection of new media and performative culture, where unfamiliar technologies are staged to feel simultaneously revelatory and emotionally resonant.

In the 19th century, if the working class wanted to learn about scientific and technological progress, they would most likely visit a fair. At a time when media coverage was not yet developed and most of the population was illiterate, people could access information about the world through anatomical cabinets, mechanical theatres, and illusionists' booths. Geographical, medical, and physical discoveries were presented in the most spectacular and entertaining ways. For example, the movements of the planets were performed by "professors" and their assistants, and this exhibition was located next to food stalls selling delicacies and a display of freaks, or so-called "wonders of nature". The latest scientific and technological innovations were exhibited as peculiar devices with which people could interact. Back then, these devices were considered magical. The telephone, photography, and even instruments such as barometers and microscopes were presented as "scientific miracles" (Wynants, 2020, p. 20).

The histories of performance and media are full of examples of objects that appear magical, sacred, or supernatural. These objects transcend their instrumentalization and have the power to pull the spectator out of the secular world. Endowed with "auratic" powers, these objects are not mere human possessions, but rather "actants", serving as intermediaries between fact and fiction (Rioult, 2023). These objects allow connoisseur viewers to "touch time", experience the past in the present, and imagine new futures. They transport their own contexts—archaeology, archives, ethnology, folklore, and fiction—with them. However, to become "charged," an object must be marked and activated by a spectator who recognizes its significance (Wynants, 2023). This marking can be understood as the object's story or context, which may emerge over time or be introduced by a performer (e.g., someone who tells visitors a story about the object). Moreover, as in magic performances, the spectator must actively engage with the performance; otherwise, the magic will not work.

An art piece needs a spectator to make an impact. Similarly, demonstrators become lifeless piles of materials if no audience engages with them. They should be displayed in places where people are open to exploration and surprise, for example, in barber shops, they might go unnoticed. Moreover, people must interact with a demonstrator to fully immerse themselves in its story; merely reading about it or watching a presentation video does not provide this experience. In many ways, the experience of demonstrators is similar to that of charged objects. Scholars studying charged objects claim that knowing too much about them deprives them of their charge and leads to objectification. Furthermore, some argue that these objects cannot be designed. Similarly, some sociologists claim that boundary objects can only appear when several groups of people recognize their meaning. However, if magicians can invent their performances, then designers can create demonstrators. Illusionism is fantastic, but a science fiction approach is also possible. Furthermore, a designer alone cannot ensure the successful recognition of a message; the viewer must also play a role.

1.4 Manifesting the future

Critical design practices are oriented toward the future. Dunne and Raby (2013) emphasize that they are only interested in the near and distant future because "future predictions have been proven wrong time and time again when it comes to technology" (p. 2). Furthermore, they suggest that scenarios should be intentionally simplified and not taken as instructions. Figure 1.1 illustrates their area of interest, which extends beyond mere forecasting to imagining the impossible. Significantly, the "preferred" future that design is supposed to be concerned about stays almost entirely outside the scope. Although critical design objects may appear concrete enough for direct use, they are far from "final". In fact, the stories they accompany would be better off never coming true.

It seems that prototypes focus on the foreseeable future because they aim to steer a conversation around a proposed solution to a problem. They may resemble objects or take the form of diagrams and collections of Post-its, meaning that they are somewhere in the middle in terms of concreteness and fidelity. Finally, demonstrators focus on currently available tools and offer practical solutions for discussion. Unlike critical and speculative design, demonstrators do not convey a critique, but rather a proposal. We would say that, by placing demonstrators at the beginning of this spectrum, they use optimistic provocation, as their goal is to shorten the distance between the problem and the audience through the proposed solution.

Demonstrators translate imagined scenarios into physical forms that align with current technological capabilities. They can be seen as examples of design fiction, a term Bleecker (2009) defines as "a conflation of design, science fact, and science fiction" (p. 6). These artefacts offer tangible experiences – such as riding 3D-printed metal bike (Boruslawski, 2016), assembling components through augmented reality (ground-eight.com, n.d.), or clearing landmines with a large tumbleweed (Minekafon.org, n.d.) – even if the concepts remain impractical: personal 3D metal printing is still limited, the range of assemble-able parts is narrow, and wind-driven devices are inefficient. Nevertheless, design allows us to envision future possibilities, evaluate current conditions, and propose preferable alternatives. Demonstrators combine imaginative thinking with practical application, fostering dialogue across different fields and encouraging inquiry into technological, communicative, and social challenges.

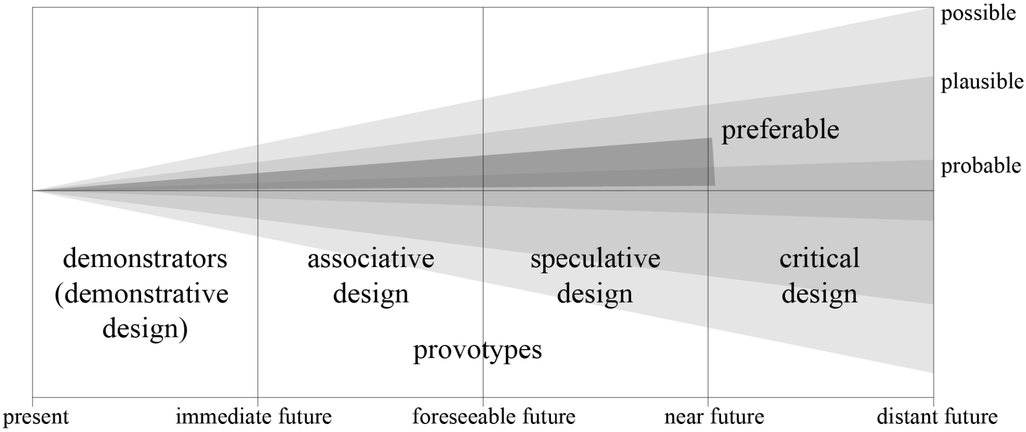
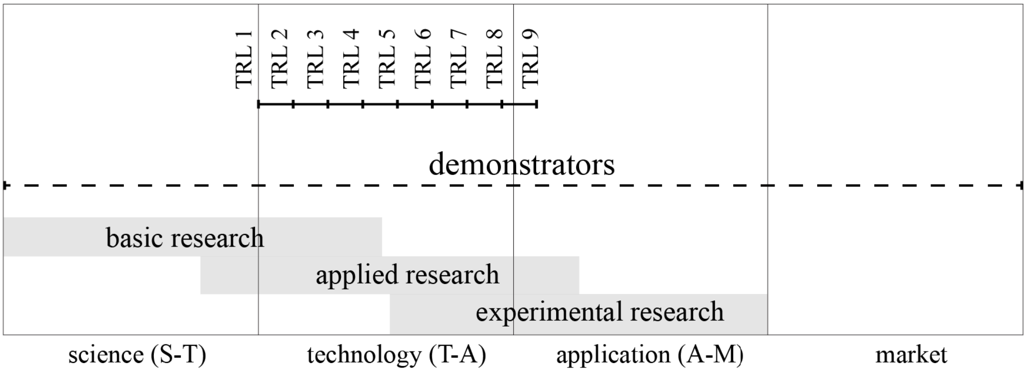


Figure 1.1. Demonstrators on the timeframe of critical design practices. Based on Dunne and Raby (2013).

Surprisingly, the most common models showing the relationship between research stages and technology development end with market distribution and do not represent how far in the future it might reach. All stages of the TRL model can be considered as applied research, slightly overlapping with basic and experimental research (Figure 1.2). That said, only moonshots can cover all the stages while focusing on the future. In this regard, they are perhaps the most versatile concept because they can consist of many types of deliverables, ranging from objects to legislative documents and national programs. Technology demonstrators can be used at any stage. In order to appear convincing, they should be of decent fidelity and somewhat "concrete"; however, the scenario they communicate is only one possibility.

Figure 1.2.
Tentative comparison of research stages based on STAM and TRL models. Based on Moultrie (2015).



1.5 Discussion and conclusions

Although it is tempting to describe the range of ideas between the "abstractness" of an idea and the "concreteness" of a solution prototype, the broadness of this notion might also lead to confusion. This chapter explores the differences between various notions that are often generalized as prototypes. Moonshots are groundbreaking programs that aim to radically improve a significant, widespread problem rather than achieve modest, incremental gains. Provotypes are deliberately surprising models that expose hidden problems or spark debate. Demonstrators transform new technologies into tangible experiences that people can engage with, making future possibilities feel real. According to the perspectives of industry and critical design practices, they are on the overlap between the present and the future: they look “final” enough to represent the immediate future, but they only serve to spark discussion because they are just one possible scenario. Due to this communicative objective, demonstrators rely on storytelling methods. Unlike critical design practices, which use objects as props to convey a certain scenario, demonstrators use stories to help the audience understand the topic. Demonstrators and provotypes not only bring tacit knowledge to materiality and phenomenological space by revealing the underlying principles or mechanisms of emerging technologies, but they also spur creative problem-solving and elicit valuable feedback from multiple audiences. By embodying scientific ideas in forms that resonate across disciplines, they envision a future with iterative refinements of technology and broader application scenarios. This ultimately nurtures the shared understanding and commitment required to bridge research insights and real-world innovations. Seen as boundary objects, they balance two tasks at once: they prove that something can work yet leave room for different groups to imagine what it could become. Although methods of storytelling seem crucial to demonstrator design, they differ from practices used in critical design. One possible direction for future research is to expand the scope to adjacent areas and explore how such methods work in charged objects design or media design, for example.

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2. Deliberately abstract: the tactics of low-fidelity prototyping

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2.1 Introduction

Why should someone deliberately choose to prototype less-complete artefacts with less detail? Are rough, low-fidelity (lo-fi) prototypes inferior to refined, high-fidelity (hi-fi) prototypes? Navigating fidelity between abstractness and concreteness, we explore the complex practice of designing the abstraction in lo-fi prototypes. Prototyping is gaining new attention as a fundamental design practice, and its "quick-and-dirty" practices appear in many design fields. However, they are mainly discussed in isolated disciplinary forms and under different terms.

To bring the discourse of fidelity in design together and reconceptualize low-fidelity, we explore lo-fi prototyping across four design fields: (a) human-computer interaction (HCI), (b) product and industrial design, (c) architecture, and (d) critical and speculative design. Our study examines how lo-fi prototyping is discussed in academia regarding its use in professional design practice at agencies, studios, and companies, as well as within design research institutions.

Methodologically, we reconceptualize lo-fi prototyping through a theoretical integrative review of different prototyping tactics in the four design fields, also shaped by our experiential knowledge as design researchers trained in (expanded) product design.

This chapter builds on our EKSIG conference contribution, "The phenomenon of low-fidelity prototyping – An overview across design practices making deliberately simpler models" (Brändle & Schuster, 2023) and develops our central argument further. We question lo-fi prototyping both as an inferior state and as a necessity when high-fidelity is not yet possible. The argument we elaborate below proposes lo-fi prototyping as a deliberate design decision of abstraction to intentionally create *open* artefacts. Designing such openness in prototypes demands specific prototyping skills – *prototyping literacy* – that enables designers to reflect and prototype intentionally.

Before we start, we need to define the key terms (e.g., prototyping, fidelity) in the form of an experimental pre-understanding to enable a discussion beyond disciplinary boundaries, including comparing terminologies. We cluster different tactics of lo-fi prototyping practiced in the four design fields. Building on that, we discuss four discourses on low-fidelity, each highlighting a part of the prototyping literacy needed in design practice as well as in design research spanning situated interpretation, non-linearity, openness, and materiality.

2.1.1 Prototypes and prototyping

It is not an easy task to define prototypes because of their flexible and heterogeneous character. Different design disciplines have different notions of prototyping and thus develop different expectations of prototypes (Houde & Hill, 1997, p. 368). Prototypes can be understood as "an incomplete portrayal of a design idea" (Lim *et al.*, 2008, p. 7), "physical manifestations of ideas or concepts" (Sanders & Stappers, 2014a, p. 9), or "representations of a design made before final artifacts exist" (Buchenau & Suri, 2000, p. 424). Adenauer and Petruschat (2012) point out the processuality of prototypes when speaking of prototyping instead of prototypes (p. 36).

In our expanded understanding, we have defined prototypes as follows (Brändle & Schuster, 2023): "Prototypes [are] artefacts created in the design process. They are specific forms of tangible and concrete models serving various purposes" (p. 187).

Only a few overview texts (Adenauer & Petruschat, 2012; Camere & Bordegoni, 2016; Exner *et al.*, 2015; Ferraris, 2023; Kannabiran & Bødker, 2020; Lim *et al.*, 2008; Wensveen & Matthews, 2014) discuss prototyping across different design disciplines. Kannabiran & Bødker (2020) emphasize that "different prototyping techniques enable different modes of inquiry with varied intentions and outcomes" (p. 1621). Regarding its purpose, the prototype takes on different roles in different situations. Beyond the well-discussed testing role of prototypes, Lim *et al.* (2008) argue for a diversification of their roles; designers and design researchers can "evolutionarily learn, discover, generate, and refine designs" (p. 2) through prototyping. Not only do prototypes serve ideation, evaluation, and presentation, but they also engage different audiences, including users, clients, and team members, and even as a reflection tool with oneself.

2.1.2 Fidelity and low-fidelity prototyping

The fidelity of prototypes is a concept rooted in HCI. Fidelity is described in numerous ways as the "resolution" (Lim *et al.*, 2008, p. 3), the "precision of a prototype" (Beaudouin-Lafon & Mackay, 2007, p. 1008), the "level of realism" (Yang & Epstein, 2005, p. 652), or the "level of refinement or degree of detail displayed by a prototype" (Blomkvist & Holmlid, 2011, p. 5).

Representative relations between prototype and product are evident in definitions such as the "level of correspondence with the product-to-be, i.e. the quality of the representation that the prototype offers" (Camere & Bordegoni, 2016, p. 157).

One of the central images for understanding fidelity is the "filter" (Lim *et al.*, 2008, p. 3). Through filtering, some dimensions of the future product (such as form, function, or experience) are filtered out in the prototype, whereas some others are manifested. Keeping in mind that all prototypes filter, fidelity is quantified in comparison: A lo-fi prototype has filtered out more dimensions compared to a hi-fi prototype.

We scrutinize traditional understandings of fidelity and problematize its conceptualization as a low-resolution representation. *We see lo-fi prototyping as a decision to intentionally create abstraction to* *use the potential of open artefacts even though a higher degree of fidelity would be possible.*

2.1.3 Terminological differences

As shown in our previous work (Brändle & Schuster, 2023), lo-fi prototyping is a fundamental practice in many design fields but is unequally labelled and discussed under different terms (pp. 188-193). Connections between different design practices are rarely made. We chose to draw connections of lo-fi prototyping practices among the fields of HCI, where the academic discourse has been most extensively developed, product design, and architecture. Enriching the discourse with further perspectives, we added speculative design as a relevant field to our study by framing the abstract models of critical practices as lo-fi prototyping. These fields were selected because they include physical as well as digital artefacts and cover opposing ends on the axis of applied versus artistic design practices, thus serving different purposes of prototyping.

Quick-and-dirty prototyping, props, mock-ups, click-dummies, paper prototyping, proportion models, wireframes, or low-tech prototypes are an incomplete list of terms describing lo-fi prototyping as either synonyms or specific examples of the phenomenon. Often, discipline-specific variables appear in the term that refer to a material or technology (paper, low-tech), a dimension (proportion, function) or a purpose of the prototype.

The term lo-fi prototyping is rarely used in architecture and product design since "models" are more common than prototypes. However, the tactic of deliberately simpler models has long been in practice. Shaped by engineering culture, in product design, only the final model is traditionally called a prototype. In design research, the open and vague term "artefacts" is often used for explorations beyond traditional products. The prototypes in speculative design are described as artefacts from the future. These "props for non-existent films" (Dunne & Raby, 2013, p. 89) use the approach of design fiction. The design tactic of abstraction is mentioned far more often in this field than the term low-fidelity. The "reduced physical design languages devoid of details" (Dunne & Raby, 2013, pp. 117-118) of these prototypes and their deliberately chosen model aesthetics stem from the choice of designing some dimensions in low-fidelity, whereas other dimensions are high-fidelity (Figure 2.1). We, therefore, propose viewing carefully crafted abstraction – achieved by leaving dimensions out – through the lens of low-fidelity prototyping too.

Figure 2.1. Prototype of a smart object in a film, showing abstraction through monochromatic design. Note: From *Uninvited Guests*, by Superflux, 2015. Superflux (https://superflux.in/index.php/work/uninvited-guests/#).

2.2 Low-fidelity prototyping tactics

Through an iterative clustering of the literature body, we identified various tactics used by designers prototyping with low-fidelity. These tactics describe specific practices, highlighting the different purposes and effects of lo-fi prototyping. Some tactics are more common in certain design fields than others, revealing disciplinary prototyping conventions. This overview should help dive deeper into specific terms, bring together overlapping patterns, enrich the different disciplinary practices, and diversify the different areas of application and purposes.

2.2.1 Acting pragmatically and ad hoc

From a technical and pragmatic approach, lo-fi prototyping in HCI is discussed as a "matter of cost" (Lim *et al.*, 2008, p. 4). It is emphasized as a cheap, quick, and efficient approach, coined in the term "quick-and-dirty prototyping" (Camere & Bordegoni, 2016, p. 155), which communicates limited time and imperfection. The time factor was also central in the 2000s term of "rapid prototyping" referring to fast digital manufacturing, rarely also applied to analogue lo-fi prototyping. In product design, pragmatism is discussed as an “ad hoc” approach, using whatever available material (Frye, 2017) to design a “good enough” version.

2.2.2 Filtering to focus

Returning to the notion of the filter, designers use this characteristic of prototypes tactically. It is often described as a focus, as Lim *et al.* (2008) point out: “The designer screens out unnecessary aspects of the design so that they can extract knowledge about specific aspects [...] more precisely and effectively” (p. 3). In Wong’s (1992) concept of “rough and ready prototypes”, issues not for discussion are represented in a low-resolution form, allowing focus on a single question (p. 83). In user testing, lo-fi prototypes can minimize critique of irrelevant dimensions, such as distracting formal-aesthetic properties like font, colour, or shape, and steer the investigation in a desirable direction.

2.2.3 Talk-back reflection

In the “dialogue” between designer and prototype, there is an iterative process of what the designer sees and how the material’s limitations direct thinking. These “talk back” situations (Schön, 1984, p. 79) are a reflective tool in solo prototyping, especially in lo-fi prototyping, due to the ease of fast manipulations. This can also be used in participatory formats to initiate a back-and-forth process with the materials at hand and emerging associations.

2.2.4 Failing and learning

To fail fast, fail often is claimed in agile innovation and design thinking processes, as promoted by Thomke (2003, p. 211). Less pointed, but just as widespread in practice, in HCI and product design practices prototyping follows a “try early and often” mindset. Trying ideas out quickly through lo-fi prototyping helps avoid designing too intensively in the wrong direction. This paradigm shift aims at destigmatizing failure as failing allows learning. Beyond this economically driven approach, encouraging experimentation emphasizes the epistemic quality to learn through prototypes in research-driven processes.

2.2.5 Scaling up – scaling down

Architectural scholars describe specific tactics referring to the scale of buildings and models. Yaneva (2005) points out an oscillation between scaling up and scaling down. Scaling down refers to intentionally making smaller-scale models to "evoke things and make broader assumptions", while larger counterparts illustrate sizes, shapes, and precise positions (p. 880).

2.2.6 Reconfigurable and evolutionary prototypes

Only some lo-fi prototypes are iterated into further prototypes. "Throw-away prototypes" in HCI, following Bähr (2012, p. 90) and Kordon & Luqi (2002), are less complex to make, so the building effort is manageable. "Evolutionary prototypes", by contrast, allow for future iterations, possibly by choosing a (digital) medium close to the envisioned final product so that prototypes can be reprogrammed and iterated without starting over (Bähr 2012, p. 90; Kordon & Luqi, 2002). Both approaches can be applied in lo-fi prototyping, with evolutionary prototyping also including analogue materials that are re-tinkered or newly combined. In collaborative prototyping, the iteration of evolutionary, possibly reconfigurable, lo-fi prototypes allows others to comment on their perspectives by modifying design elements of the prototype.

2.2.7 Combining multiple prototypes

Since all prototypes filter, and decisions must be made about which dimensions to emphasize in a lo-fi prototype, the tactic of combining several prototypes can be applied. Creating multiple prototypes for one situation (such as a client presentation) is a way to address the limited scope and purpose of a single prototype, either with varying fidelity or several with (different) low-fidelity. Barati *et al.* (2019), e.g., combined a lo-fi tool to experience the function and a hi-fi smart material demonstrator (p. 34). Different prototypes can highlight different dimensions and thus different questions.

2.2.8 Experience prototyping

When designing complex systems, not only do prototypes manifest physical or digital artefacts, but they also lend themselves to processes,

interactions, and experiences. “Experience prototypes” are used with a “low-fidelity mindset” (Buchenau & Suri, 2000, p. 431), especially in service design and tangible interface design in HCI. This can include “bodystorming” (Oulasvirta *et al*., 2003), incorporating the body through role-play into the lo-fi prototype. Flechtner *et al*. (2020) employ such an embodied and performative approach to co-prototype a wearable soft robotic orthosis with an assembly-line worker (Figure 2.2).

Figure 2.2.
Lo-fi prototype of a wearable soft robotic orthosis for communicating needs and requirements during a workshop with users.
Note: From “Designing a Wearable Soft-Robotic Orthosis: A Body-Centered Approach” by R. Flechtner, K. Lorenz, and G. Joost, in *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI ’20)* (p. 867), 2020, Association for Computing Machinery.

2.2.9 Props and simulation

Lo-fi prototypes are widely used for simulating more than they are in all covered design fields. The term “mock-up” describes their use as imitations and props for presentation. It communicates its theatrical yet unfinished character, originating from its French origin “maquette”, meaning unfinished draft or sketch (Colonnese, 2016, p. 291). The magic of simulation is captured in the HCI term “wizard of oz prototypes” (Beaudouin-Lafon & Mackay, 2007, p. 1008), where technical functions are simulated as a kind of trick. Frequently, available materials are used to stand for other materials.

2.2.10 Lo-fi prototypes foster discussion

The communicative quality of lo-fi prototypes to encourage dialogue is emphasized by many scholars across all design fields. A prototype with a high-perceived finishedness can block the productive discussion of a design (McGrath *et al.*, 2016, p. 722). The deliberate use of more abstract sketches instead of renderings is documented to avoid situations where "a perfect model seems to be complete and somehow locked to suggestions" (Bähr, 2012, p. 90) and, therefore, lo-fi prototyping is a protection from criticism regarding feasibility (Dunne & Raby, 2013, p. 106). Low-fidelity communicates that the artefact is only "a proposal–provisional and open to change" (Lim *et al.*, 2008, p. 18). The abstractness of lo-fi prototypes opens up communication spaces, as it leaves space for interpretation, not only in prototyping for debate in speculative design but also in solution-oriented design practices.

2.2.11 Provoking and irritating

Especially in critical-speculative design practices, designers provoke and irritate through prototypes. This can be achieved by the visual language of the "aesthetics of the unreal", which aims to represent the real and the unreal simultaneously (Dunne & Raby, 2013, pp. 101-138). Designing abstraction in lo-fi prototypes can lead to *productive* misunderstandings because of their ambiguity (Gaver *et al.*, 2003). Carefully crafted ambiguous artefacts, "provotypes" (Mogensen, 1992), or lo-fi prototypes that create friction and limitations (Tost *et al.*, 2022) are all tactics in this realm.

2.2.12 Exploration beyond solutions

Prototyping is increasingly used beyond the development of solutions, serving as an exploratory tool (Sanders & Stappers, 2014b), and lo-fi prototyping is particularly suited for this purpose. The concept of "exploration-through-prototyping" (Camere & Bordegoni, 2016, p. 155) is used especially in HCI and participatory design research to focus on requirements and needs (Flechtner *et al.*, 2020), as well as on questions, problems, and systems, including prototyping anxieties and visions, as Schuster and Peukert (2024) show. Similarly, Ratto's (2011) "critical making" emphasizes critical thinking through designing artefacts. Lo-fi prototyping here becomes a non-linguistic instrument of inquiry to approach complex topics, a practice found in speculative design, where speculations through prototyping explore the problem space.

2.2.13 Toolkits in co-design

As design becomes more participatory in several fields, different tactics of prototyping with people from non-design backgrounds are applied, from focused user-centred design in applied product design, architecture, and HCI to more open-ended participation in social design or speculative practices. Influenced by the rise of service design and design thinking, the use of co-design methods has increased. To embed lo-fi prototyping in these contexts and guide participants through co-design formats, toolkits come into play. Khan & Matthews (2019) develop such a toolkit as a "constructive assembly", a reconfigurable, modular, physical set of basic materials (p. 155) which ensures participants to "never start from nowhere" (p. 160). The balance between the structure of toolkits and the freedom to prototype, including material selection, is crucial when designing such formats. The low-fidelity approach lowers the barrier for participation, as participants can quickly make their visions tangible using materials that are inclusive and easy to work with.

2.2.14 Playfulness

The tinkering of lo-fi prototyping across all design fields allows for playfulness, or what Schrage (2013) calls "serious play" (p. 25). According to Schrage, prototyping is a playground because what is built is not yet real. Suspending rules and norms allows us to imagine the world differently, and experiment and play through alternatives. We consider such creativity, fantasy, playfulness, and the not-so-banal fun to be central qualities of lo-fi prototyping. These exist in a tension field with professionalism that should be reconsidered.

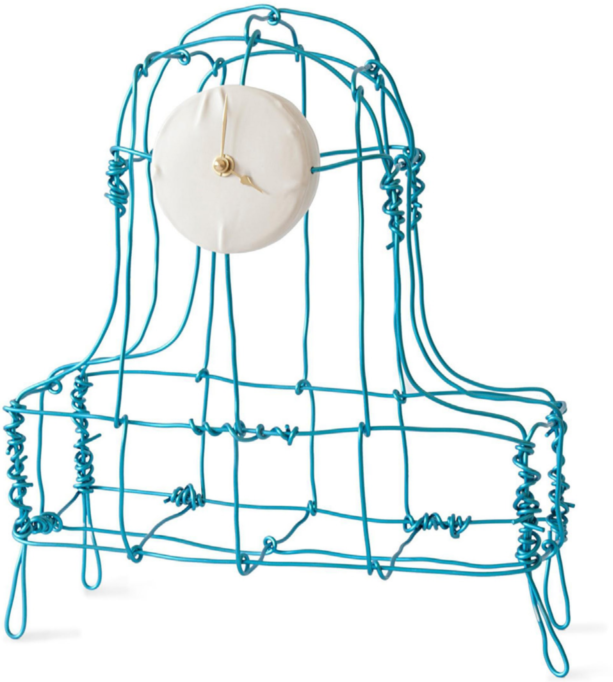
2.2.15 Serendipity

Prototyping processes cannot be fully planned. Drawing on the concept of "bricolage" (Lévi-Strauss, 1973), Frye (2017, p. 149) describes improvisation in product design when designing and prototyping. Surprising findings – serendipity – arise from situations and the materials at hand. Acknowledging this unpredictability is not opposed to well-reflected and structured processes; it is a feature of lo-fi prototyping that is helpful to be aware of and can be intentionally exploited.

2.2.16 Processual aesthetics

The process that leads to a product plays a far greater role today. The process itself becomes part of communication (Frye, 2017). Featured making-ofs by author-designers in product design emphasize the organic process of designing a product and thus show early, unfinished models that would have been hidden. This can even lead to low-fidelity prototyping being deliberately employed as a stylistic device in finished products, as Frye (2017) illustrates through the work of van Eijk (Figure 2.3).

Figure 2.3.
Kiki van Eijk's *Floating Frames Sculptures*. Note. From *Floating Frames Sculptures* by K. van Eijk (2013). Kiki and Joost (https://kikiandjoost.com/kiki/portfolio_page/floating-frames-sculptures/).



2.3 Discourses: developing prototyping literacy

In Brändle and Schuster (2023, pp. 193-197), we clustered discourses around lo-fi-prototyping in four main topics:

1. Scrutinizing the technical binary distinction between low- and high-fidelity.
2. Deriving how lo-fi prototyping becomes a mode of creating openness through abstraction.

3. Discussing the non-linear development of fidelity during the process.
4. Exploring interdependencies between fidelity and materiality.

Building on these, we aim to show lo-fi prototyping as both an epistemic practice and a source of situated knowledge behind this practice. By revisiting our discourses, we argue for the urgency of a prototyping literacy.

While there are debates that include prototyping as a key skill within broader design literacy (Jessen & Quadflieg, 2023, p. 96), this concept can be further refined by highlighting prototyping literacy as a distinct, cross-disciplinary competence. Prototyping literacy involves the ability to design, interpret, and reflect on prototypes *for* and *with* different audiences and purposes. Designers should be able to navigate the space between abstraction and concreteness. Therefore, fidelity plays a crucial role in designing prototypes. Instead of generalizing the use of hi-fi or lo-fi prototyping, these design decisions must be made in a highly situational way for each project. Prototyping literacy highlights the importance and value of designers and design researchers in transdisciplinary projects.

2.3.1 Fidelity: from technical dimensions to situated interpretations

With its origin in HCI, the term "fidelity" began as a technical attribute of prototypes, extensively discussed in the "high-vs-low-fidelity debate" (Houde & Hill, 1997; McCurdy *et al.*, 2006; Rudd *et al.*, 1996; Wong, 1992; Yang & Epstein, 2005). HCI scholars further dissected fidelity in "scope and resolution" (Lim *et al.*, 2008, p. 11) or "breadth and depth" (McCurdy *et al.*, 2006, p. 1235) of a prototype. Even with more specific terminologies, the initial binary distinction between high and low failed to reflect real-life practices. "Mixed fidelity" (McCurdy *et al.*, 2006, p. 1235) emerged as a concept to describe differing fidelity (some high, some low) of different dimensions within one prototype, mostly referring to a "mid-fidelity" in the middle along the axis. However, we see mixed fidelity as a more nuanced conceptualization of all prototypes overcoming the binary.

As we previously showed in more detail, "fidelity is not an objective property of an artefact that is clearly readable by its appearance" but must be seen as an interpretation (Brändle & Schuster, 2023, p. 194).

It can no longer be linked to the degree of interactivity, as Rudd *et al.* (1996, p. 78) did, or any other single dimension. There are always multiple ways to conceive and perceive prototypes. This can be derived from the question of what can be seen as a prototype at all. Following scholars from more recent model theory, it is the consequence of seeing something as a model that makes it a model (Mahr, 2008, p.199). Applied to low-fidelity, multiple people must agree on what they regard as low-fidelity in one specific prototype. Revisiting our discourse of fidelity as interpretation (Brändle & Schuster, 2023, p. 194), we see an ongoing shift from traditional definitions of lo-fi prototypes and fidelity as a technically described dimension to fidelity as interpretation and abstraction based on situated skills. The perceived fidelity of the materials or functions of a prototype can only be interpreted in relation to the thing the prototype represents and to the people involved in the specific context.

As there is no universal recipe to mix fidelity the right way, "fidelity trade-offs" (Barati *et al.*, 2019, p. 27) must be made. Building on the tactic above of "filtering to focus" (Section 2.2.2), designers consider which dimensions should be prioritized, such as visual or performative qualities. Diefenbach *et al.* (2013) assume that these decisions are mostly made by accessible tools, materials, and routines, rather than actual reflections (p. 54). Prototyping literacy would make such decisions conscious and includes, as Blomkvist and Holmlid (2011, p. 5) emphasize, the designer's skill of abstraction and their estimation of the ability of the audience to interpret prototypes.

2.3.2 Opening communicative and epistemic spaces through lo-fi prototyping

Earlier perspectives on lo-fi prototyping emphasized filtering out unnecessary or undefined dimensions to focus attention on key dimensions. In contrast, contemporary perspectives value the ambiguity inherent in well-crafted abstraction, seeing it as an opportunity to explore uncertain areas. This shift moves lo-fi prototyping from concealing to revealing, with both approaches holding merit depending on the context.

The more organic process of deliberately using a lower fidelity to create openness has been known at least since the Renaissance, as described by Lepik (1995) regarding Michelangelo's model of St. Peter's Cathedral. Using less detail is leaving the scope of action open, rather than imposing authoritarian effects of an overly detailed model (Bredekamp, 2008). Similarly, in HCI, fidelity determines whether a prototype serves as a living specification to implement or an open platform for discussion (Rudd *et al.*, 1996, p. 84). Fidelity is described as a central aspect to achieve this openness (Rudd *et al.*, 1996, p. 84) and prototypes are designed "deliberately incomplete" (Barati *et al.*, 2019, p. 34). Avoiding excessive realism and deliberately crafting ambiguity, as discussed by Dunne and Raby (2013), creates "space for interpretation" (p. 106).

This openness as a space for interpretation enhances the previously described tactic of "lo-fi prototypes foster discussion" in section 2.2.10. Crafting openness is, therefore, central in our reconceptualized perspective on lo-fi prototypes. Wong (1992) specifically mentions that lo-fi prototypes facilitate communication "on high level issues" (p. 83). In research-oriented design, the focus on ambiguity is widely used as a tactic, especially in participatory inquiries. For example, Flechtner *et al.* (2020) used elements with enough abstraction in their bodystorming lo-fi prototype for a wearable soft robotic orthosis (Figure 2.2), allowing the assembly workers to interpret and discuss the placement of different functions on their arm (p. 866).

Lo-fi prototyping as a tactic of crafting openness for the communicative spaces serves two main purposes. First, it can build consensus (Khan & Matthews, 2019, p. 156), even across disciplinary boundaries, by acting as a "boundary object" (Star & Griesemer, 1989) that helps to develop shared visions (Kannabiran & Bødker, 2020, p. 1624). Second, openness can deliberately generate misunderstandings, evoke multiple interpretations and visions (Gaver *et al.*, 2003; Kannabiran & Bødker, 2020, p. 1624), and challenge established perspectives, building on the tactic of "provoking and irritating" (Section 2.2.11).

Whether aiming for consensus or diversity of perspectives, the openness in lo-fi prototyping depends on the designer's skill to craft meaningful abstraction – a central aspect of prototyping literacy. For instance, a participant in a co-design workshop created a highly abstract prototype of a "slow bus station" (Figure 2.4) with simple lines, foam, wire, and moss. Lo-fi prototyping was used to spark debate on transportation conventions, jointly develop the concept further, and inspire alternative thinking.

Figure 2.4. Prototype showing a slow-bus concept in a speculative city of the future by F. Thomet, outcome of the hybrid participatory workshop The Other City 2 led by J. Tost, P. L. Schuster, R. Flechtner, K. Budinger, and F. Heidmann for PROTOTYP, a design research project at FH Potsdam in 2021.

However, while higher fidelity does not necessarily yield deeper insights (Diefenbach *et al.*, 2013, p. 54), a low fidelity may hinder informed insights when a prototype is too abstract for a specific situation. Additionally, since the usage of a prototype usually works in conjunction with language, one pitfall is to depend on overly detailed verbal explanations to compensate for the unreadability of too low fidelity, thereby closing the open space again with words.

Scholars have drawn analogies from the ambiguity in designerly prototypes to experimental systems and *epistemic things* (Knorr Cetina, 1998; Rheinberger, 1997) in science studies. Opposed to instruments as technical things, epistemic things are considered as "unfoldable" artefacts for exploring new possibilities (Knorr Cetina, 1998). While this seems similar to how lo-fi prototyping creates openness, Oder (2020) points out the difference between epistemic things and what he calls "entwerferische Dinge" [designerly things]. While scientific inquiries aim at resolving ambiguity and overcoming vagueness (Rheinberger, 1997, p. 49) to produce knowledge, following Oder (2020), designerly approaches actively craft ambiguity and vagueness to open up new perspectives. Open lo-fi prototyping is mostly not meant to prove statements, but as Petruschat (2019) points out, ambiguity in design processes helps to search different possibilities (pp. 230-231). Therefore, prototyping literacy includes creating ambiguity for epistemic purposes.

2.3.3 Scrutinizing the linear increase of fidelity and representational relation

Lo-fi prototyping is commonly associated with the early stages of the design process. However, fidelity does not necessarily increase linearly from one prototype to the next (Brändle & Schuster, 2023, p. 196). Low-fidelity prototyping is not merely done out of necessity when high-fidelity prototyping is not yet possible. Rather, we argue, it is a deliberate choice that can be strategically employed at any stage of the design process. While the vision of the final thing becomes richer and clearer over time, a prototype is more than an image with increasing resolution.

Back to the representation paradigm we discussed in 2023 (Brändle & Schuster), the non-linearity can be derived from model theory (p. 196). Overcoming the representation paradigm means that models are more than simplified representations of an original. They are not objective reductions, and the model's purpose is not better fulfilled by the quality of how well a model can represent an original (Wendler 2013, p. 49). Instead, we adopt the view that models construct reality (Petruschat 2019, p. 232), and prototypes, therefore, construct the product. Thus, lo-fi prototypes should not be seen as minor representations but open, active tools with constructive potential. Speaking of "designing" prototypes instead of "building" is even more fitting, as it highlights the design decisions behind them.

We conclude that lo-fi prototyping is a fundamental design tactic that can be applied at any stage, not just as an intermediate step or when shifting directions. The earlier described tactics of "scaling up-scaling down" (Section 2.2.5) and "processual aesthetics" (Section 2.2.16) demonstrate that a lower fidelity can appear even in later phases, challenging the notion of a linear progression.

Adenauer and Petruschat (2012) propose a perspective on things as permanent beta: Prototyping becomes a mindset to see everything changeable while at the same time building on what was already there (pp. 32–34). In this view, lo-fi prototyping is not merely a preliminary step on the road to refinement; it is a distinct mode of reflective inquiry.

It becomes a deconstructive way to criticize and restructure, which we know especially from speculative design. As Janda (2018) notes, the prototype creates uncertainty about the “taken for granted” status quo (p. 164, 209). In design research, this lo-fi mode of inquiry can be applied at all stages, too. Products are prototyped; however, the contribution often lies not in the product itself but in what the product illustrates, such as opening a space of interactive design possibilities (Wensveen & Matthews, 2014, p. 3). In these experiments, prototypes become research instruments in the form of physical hypotheses (p. 4), for open-ended explorations of unsettled design or use spaces, as intervention in the world to study the consequences (p. 8), or the process of prototyping itself as the vehicle for inquiry (p. 3).

Prototyping practices, including those in research contexts, are shaped by industrialization, thus carrying capitalist imperatives: productivity, time pressure, efficiency, utilization logics, and the expectation to innovate and generate output. Lo-fi prototyping practices in this context are limited by several factors, resulting in very little or no lo-fi prototyping at all. First, an agile mindset fosters the use of lo-fi practices but in very quick sprints as a cost-effective approach with reduced material costs. A slower, more explorative and conscious approach – leaving space for failure and iterations, and enough time to include users in appreciative ways – is often lost to economic interests. A lack of understanding of the lo-fi practice is also fuelled by a claim for proof of performance, where the association with “proof-of-concept”, as prototypes are also called, arises. This arguing for plausibility, as Dickel (2019) assigns to prototypes (p. 48), often leads designers to present their concepts in high-fidelity. Thus, they communicate their refined design skills through the medium, reassuring clients of the probability of real outcomes and legitimate their financial value.

As prototyping is increasingly used in research to challenge existing assumptions, the process itself must evolve. Moving beyond the narrative of steadily increasing fidelity can open up new ways to address future needs and possibilities. Developing *prototyping literacy* involves understanding the processual nature of prototyping and applying prototyping for exploration at any stage of the process.

2.3.4 Active materiality and working with limitations

In lo-fi prototyping, simple and easily workable materials, like cardboard, foam, or wire, are favoured. Their popularity comes from being inexpensive and easy to shape. However, low-fidelity is not per se defined by specific, simple materials. "The ease with which a material can be deformed should not be confused with the degree of detail a material can display" (Brändle & Schuster, 2023, p. 197). Our traditions of perception are shaped by certain materials and their aesthetics, but lo-fi prototyping is not limited to these materials or any technology. It is worth reconsidering what can be used for lo-fi prototypes, including electronic or digital elements, such as wireframes or extended reality.

On one hand, the simplicity of materials has been criticized as a limitation on what can be explored through such models (Benisch in Wendler, 2013, p. 30). On the other hand, this very limitation, fuelled by the materials' low or high "resistance" (Cannaerts, 2009, p. 782), can be an advantage of lo-fi prototypes. Material limitation can lead to more expressive and creative prototypes (Khan & Matthews, 2019, p. 159).

In participatory workshop formats, someone else usually selects the materials along the axis of raw to predefined. Opposing tactics

Figure 2.5.
Workshop with foldable vegetable crates in the process of designing an organic farm in Seevetal, Germany.
Note: From *079 Gärtnerhof Overmeyer Organic Farm* by BeL & Urban Catalyst Studio, 2014. Bel (https://bel.cx/projects/).

can come into play: irritating or unconventional materials (e.g., sandpaper) versus deliberately familiar materials (e.g., Lego). A careful selection of familiar materials like foldable vegetable crates (Figure 2.5), pebbles, or blankets can encourage participation, as seen in the example of Bernhardt (2016, pp. 327-330).

This can be seen as a clear indication that even simple materials are not that neutral at all. The material shapes the ideas simultaneously with the prototyper. Supposedly abstract ideas are inner representations of physical experiences too (Petruschat, 2012, pp. 288–289). This overcomes the traditional perspective of bringing ideal shapes from the designer's mind into the material, represented in minor form, thus highlighting the material agency.

The materiality of lo-fi prototyping is sometimes perceived as crafty or as ordinary tinkering. Lo-fi, craft-like prototypes can indeed result from missing craft or technological skills – or merely appear so. Prototyping with low-fidelity, however, is a skill of using materials as more than they are (by using the tactic of "props and simulation" as introduced in section 2.2.9), whether early in a project or later as mock-ups or speculative objects.

Considering that the materiality shapes the concept, material decisions are crucial and therefore part of prototyping literacy. Critically reflecting during the process, being aware of and tactically using the material agency, is essential. Next to cognitive reflection, an embodied, practical experience of "knowing how" (Ryle, 1945) in materials – the craftsmanship – is indispensable.

Following the tactic of "talk-back reflection" (Section 2.2.3), the prototyping literacy includes actively entering those talk-back situations with the materials and enabling those situations for others with lo-fi prototypes. This can happen through the tactics described in Section 2.2, like "playfulness", "serendipity", "provoking and irritating", "experience prototyping", or, in participatory formats, the tactic of "toolkits in co-design".

Thinking through hands with lo-fi prototyping is a form of inquiry that responds to structural and conceptual considerations. "Simple" materials are thought to be better suited for the ideational and communicative processes in which lo-fi prototyping is primarily used, thus providing a high potential for the tactic of “exploration beyond solutions” (Section 2.2.12). This includes designing relations, prioritizing elements, and experimenting with variations.

2.4 Conclusion

Our study shows that lo-fi prototyping is a fundamental design tactic rather than just an attribute of prototypes. Our key finding is that lo-fi prototyping needs to be a reflective practice of carefully crafted openness, which we describe as a key aspect of prototyping literacy. We are not advocating an as-low-as-possible fidelity approach to prototyping, but rather an awareness of where it makes sense to blur, abstract, or leave out details. Prototyping literacy includes choosing the appropriate level of fidelity and reflecting on both the prototyping process and the purpose of the prototype.

The prototyping tactics and the necessary knowledge are often tacit in their application. As we have shown, they are highly situated and follow certain narratives about how prototypes have to be used. At the same time, these tactics open up new, ambiguous spaces full of possibilities and enable others to participate. The tactics of lo-fi prototyping integrate materiality as an active part of the thought process, rather than treating it as a mere representational canvas. Reflecting again on the three desiderata of lo-fi prototyping as an epistemic practice from 2023 (Brändle & Schuster, pp. 198-199), we would like to specify what a prototyping literacy with a focus on low fidelity might open up for further research.

1. Learning and teaching low-fidelity prototyping in design education means learning how to deliberately use abstraction while prototyping. This can only be experienced through practice, and, due to the situatedness of prototyping processes, general rules should be avoided. Those who teach may use and transfer helpful tactics to other situations, but should be aware that they reproduce certain narratives on how prototypes are perceived and utilized. Learning through prototyping practices continues into professional life. Further considerations of the didactics for prototyping literacy hold potential for a deeper

understanding of how to acquire and mediate reflective design practices in general, including research methodologies.

2. In design research, a low-fidelity approach for the open-ended inquiry of an exploration-through-prototyping holds epistemic potential by focusing on ambiguous uncertainties. However, lo-fi prototyping in research is highly dependent on those who prototype or prepare and guide co-prototyping processes for others. Acknowledging prototyping literacy means recognizing that there are specific prototyping skills beyond standardized methods that require training, such as designing abstractness in prototypes. The design researcher's role within transdisciplinary projects – including the dynamics between designer and other researchers, participants, and material agency – holds potential for further research.
3. Extended documentation and studies on lo-fi prototypes are needed, as most available prototypes are at the higher end of fidelity. There is a lack of documentation for the fuzzy and more abstract prototypes, which are more than crafty preliminary steps or irrelevant detours but vehicles for open-ended inquiry. This includes artefact documentation and ethnographic studies of the prototyping practices. At the same time, there are challenges in verbalizing what is done during prototyping. Prototyping literacy could provide a framework to better describe and reflect on the interdependencies between artefacts, materiality, craft, and their epistemic use. This deeper understanding offers possibilities to better integrate designerly prototyping practices in transdisciplinary processes, as it can demystify these approaches while appreciating the underlying tacit knowledge.

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3. Prototyping collaboration: managing collaborative projects in design education

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3.1 Introduction

Collaborative learning is a "complex team dynamic, asking for high interdependence, shared comprehension and a definition of common objectives" (Tessier, 2021, p. 215). Precisely because of this complexity, design students in higher education are considered especially well-suited to engage in it (Mattioli, 2022; Tessier, 2021). Through developing collaborative skills, students also gain greater autonomy and enhance their social and teamwork abilities (Matthews *et al*., 1995; Tessier, 2021). Moreover, collaborative learning is often integrated into project-based pedagogy, which prepares students for real-world challenges by fostering problem-solving, decision-making, and inquiry skills – core competencies for design engineers (Deighton *et al*., 2024). This pedagogical approach also increases student motivation and engagement by bridging theoretical knowledge with practical application. When combined with collaborative learning, project-based pedagogy effectively equips students to tackle complex projects that demand diverse expertise, a clear division of tasks, and strong interpersonal and teamwork skills. These elements contribute to a well-rounded education that prepares students for professional practice.

However, collaborative learning is rarely systematically embedded in design curricula despite its potential, especially concerning teaching strategies, learning methods and assessment practices (Deighton *et al*., 2024; Green *et al*., 2022). In this context, integrating project management or agile principles (i.e., a collection of practices aimed at enhancing group collaboration) into project-based learning can help address this gap by providing concrete methods and tools to support effective collaboration (Barbosa, 2022; De Los Ríos-Carmenado *et al*., 2015; Pokharel, 2023). Agile approaches, for instance, can promote better communication and adaptability while aligning with the iterative and evolving nature of design projects (Hulshult & Krehbiel, 2019; Stewart *et al*., 2009). Both agile and project management frameworks can provide design students with real-world methods and tools for planning, tracking, and managing complex projects (Cruz *et al*., 2021). Within project-based learning environments, where students face realistic challenges, these approaches not only improve the outcomes and quality but also reinforce the objectives of design education by preparing students for dynamic, collaborative, and multidisciplinary professional settings (Cruz *et al*., 2021; De Los Ríos-Carmenado *et al*., 2015; Hulshult & Krehbiel, 2019). Furthermore, it positively affects team dynamics and individual well-being by reducing stress, preventing misalignments, and mitigating competition (Green *et al*., 2022), which, being opposite to collaboration and equally learned, creates an unfavourable condition for learning about collaboration (Kohn, 1992).

The role of design educators is fundamental in embedding collaborative and project-based learning within academic curricula. In particular, the teaching staff are responsible for clarifying the purposes and complexities of collaborative learning and for providing tools to support it (Mattioli, 2022). Continuing to integrate further collaborative methods into a project-based course within the MSc in Design & Engineering at Politecnico di Milano (Mattioli *et al*., 2020, 2023; Mattioli & Ferraris, 2021; 2024), we developed a low-fidelity prototype of a management platform using Notion that was tested in one of the two parallel sections of the Final Project Work (FPW) course during the first semester 2024/2025. This platform was designed to offer a structured framework for student teams to document and reflect on various dimensions of their collaboration and to share these insights with the teaching staff.

This chapter presents the process of designing the platform, the criteria used for its selection, how it addresses different aspects of project management and the diverse ways student teams engage with it. The aim of developing the platform prototype was to offer students a method for navigating collaborative and project-based processes while raising awareness of its relevance to their work as current and future design engineers and professionals.

3.2 Designing a low-fidelity prototype for collaboration

By designing and developing a low-fidelity prototype using Notion, we aimed to provide design and engineering students with an appropriate and intuitive method for navigating project-based learning and design team-based projects more confidently, steadily, and stress-free while developing stronger interpersonal and organizational skills. In the next section, we will explore the rationale behind the selection and design of the prototype and describe the outcome.

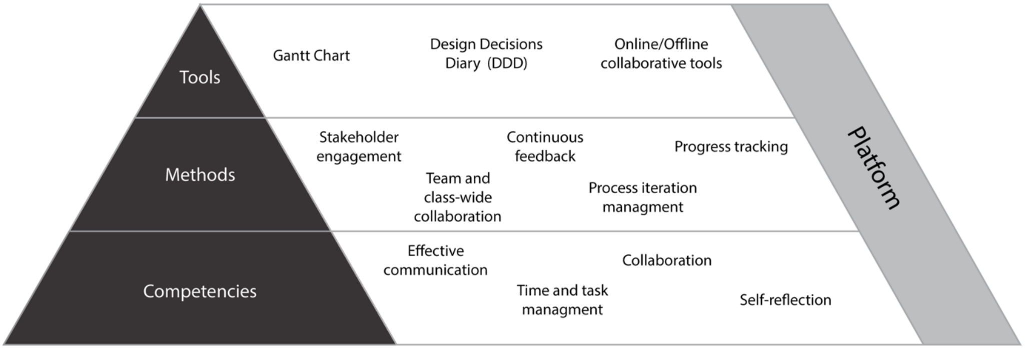
3.2.1 The competencies-methods-tools pyramid

Our method involved adapting project management best practices to a design project-based learning course, Final Project Work, in the second year of MSc Design & Engineering. Several examples across disciplines of project management frameworks adapted to learning environments (Cruz *et al*., 2021; De Los Ríos-Carmenado *et al*., 2015; Fioravanti *et al*., 2018; Krehbiel *et al*., 2017; Marnewick, 2023; Molinari, 2021; Parsons & MacCallum, 2019; Zhang, 2022) show how the value of integrating project management knowledge into project-based learning environments is starting to be recognized.

For the methodological design of the platform, we were inspired by the pedagogical model proposed by Parsons & MacCallum (2019), which adapts agile and lean methodologies to education. The model is a pyramid comprising three interrelated components: *values*, *processes*, and *techniques*. At the pyramid's base, values emphasize agency, outcomes, and continuous improvement, aligning with agile's empowerment of individuals and lean's focus on value generation (Parsons & MacCallum, 2019). As the pyramid's central element, processes incorporate learner-paced, iterative, and reflective cycles akin to agile sprints and lean pull-flow systems, fostering ownership and adaptability (Parsons & MacCallum, 2019). Lastly, at the top, techniques centre on collaboration, problem-solving, and visibility – translating agile tools like stand-ups and story cards and lean tools such as Kanban and gemba walks into educational practices (Parsons & MacCallum, 2019).

Inspired by the framework, we reframed this hierarchical categorization to align with our goals. In our reinterpretation, values are translated into a set of core student *competencies* (i.e., collaboration, self-reflection, time and task management, and effective communication), processes become the *methods* we aim to instil (i.e., stakeholder engagement, team and class-wide collaboration, continuous feedback, process iteration management, and progress tracking) and techniques are expressed as a focused set of *tools* designed to support these practices (i.e., Gantt Chart, Design Decisions Diary). Figure 3.1 illustrates our adaptation of Parsons & MacCallum's pyramid, reorganized around competencies, methods, and tools essential to our scope of fostering alignment and shared understanding of the collaborative process among design engineering students, and key in defining the required functionalities and layout of the chosen platform for our prototype.

Figure 3.1.
Our reinterpretation of Parsons and MacCallum's (2019) pyramid into the competencies-methods-tools pyramid and definition of all the components to be embedded within the prototyped platform.



3.2.2 Selecting the right fit

We evaluated seven broadly used collaborative and project management platforms (i.e., Notion, MS Project, Planner from MS Teams, Loop, Click-Up, Headrush Learning, and Asana) listed in Table 1. Based on our competencies-methods-tools pyramid, we crafted a list of functional criteria for supporting the appropriate tools (i.e., Gantt chart, design decisions diary or DDD, and offline/online collaborative tools). These tools needed to support a range of methods (i.e., stakeholder engagement, team and class-wide collaboration, continuous feedback, process iteration management and progress tracking), which, in turn, were intended to foster the identified competencies (i.e., effective communication, time and task management, collaboration, and self-reflection). We also defined accessibility as the primary exclusion criterion for the tools. To be considered, each platform had to be accessible on Macintosh and Windows Operating Systems, allow access through the institutional email account, and offer an active free or educational plan. Based on these criteria, Headrush Learning was excluded due to accessibility (i.e., lack of an active free or educational plan).

Gantt chart

We included a Gantt chart (i.e., a visual project management tool that illustrates a project schedule over time) to support the acquisition of time and task management competencies through progress tracking. Students had to assign tasks within their team, create subtasks and task dependencies, and pinpoint milestones (e.g., concept delivery). Notion, MS Project, and Click-Up were the only platforms supporting these features. For these reasons, Planner, Loop, and Asana were discarded at this stage. Moreover, to reduce complexity for students, we decided to look for a platform that could ideally embed all the listed requirements.

Design decisions diary (DDD)

DDD is an ever-updating document inspired by changelogs, where teams keep a report of their design choices over the entire project. Here, student teams collect project review feedback and observations from the teaching staff, re-elaborate them, and define the next steps. It is also a tool for the teaching staff to assess students' awareness and ability to deal with and manage the complexities of design projects.

Hence, the DDD is a tool that, through effective communication and stakeholder engagement (i.e., between teaching staff and students), aims at honing self-reflection and process iteration management competencies. First, we needed the possibility of creating templates to facilitate an initial standardization of the required contents in the DDD. Secondly, to support the assessment process, exporting the DDD file in a fixed and standard format was also a requirement. We kept Notion and Click-Up as options based on our inclusion criteria, while MS Project was directly discarded. Whereas it offers the possibility to create productivity reports, it does not provide a solution with the flexibility and adaptability we were looking for.

Offline/online collaborative tools

One of the main objectives was to make the collaborative process tangible for students and visible to the teaching staff. Collaboration is, in fact, the most fundamental competence in our framework. To help design engineering students understand and learn what a collaborative process entails, we developed our platform around team and class-wide collaboration – aiming at eradicating unhealthy competitive attitudes between teams and stakeholder engagement (e.g., between students, teaching staff, and the partner company), and continuous feedback – both from staff to teams and peer-to-peer.

To support these practices, we defined the offline/online collaborative tools as requiring the ability to allow real-time collaboration, file sharing, the creation of enough teams and team members for the number of students in our course, and the capacity to host enough participants, including students and the teaching staff team. The course included 51 students, divided into eleven groups of four to five members, and a teaching staff of five professors and one teaching assistant, totalling 57 participants. Click-Up had limitations on the number of participants, which required a plan upgrade and was discarded. Notion met all our inclusion criteria and was thus selected.

Table 3.1.
Platform selection is based on the requirements of the competencies-methods-tools pyramid. It refers to free or educational plans only.

COMPETENCE	METHOD	TOOL	REQUIREMENTS	PLATFORM						
				Notion	MS Project	Planner (MS Teams)	Loop	Click-Up	Headrush Learning	Asana
Time and task management	Progress tracking	GANTT CHART	Gantt view	✓	✓	–	–	✓	–	–
			Assign tasks	✓	✓	✓	–	✓	✓	✓
			Create subtasks	✓	✓	✓	–	✓	✓	✓
			Create task dependencies	✓	✓	–	–	✓	✓	–
			Create milestones	✓	✓	–	–	✓	✓	✓
Effective communication	Stakeholder engagement	DDD	Export to PDF	✓	✓	–	✓	✓	–	✓
Self-reflection	Process iteration management		Create templates	✓	–	–	✓	✓	–	–
Collaboration	Stakeholder engagement	OFFLINE/ONLINE COLLABORATIVE TOOLS	Real-time collaboration	✓	–	–	✓	✓	✓	✓
	Team and class-wide collaboration		File sharing	✓	–	–	–	✓	✓	✓
			Create 11 teams of 4-5 members each	✓	–	–	✓	–	–	–
	Continuous feedback		Host 57 members	✓	–	–	✓	✓	✓	–

3.2.3 Final Project Work collaborative platform

Notion is a highly customizable digital workspace with functionalities ranging from notetaking to managing teams, projects, and collaboration. Using Notion, we could integrate all the requirements to provide a comprehensive platform for design engineering students. We could also support them in managing their design projects more effectively while they learn project management methods and develop collaborative competencies.

When designing the Notion layout and pages (i.e., blank spaces that can be shaped according to one's needs and filled with a wide variety of elements such as images, text, checklists, tables, or databases, to name a few), our objective was to provide a specific space for each competence, i.e., collaboration, self-reflection, effective communication, and time and task management.

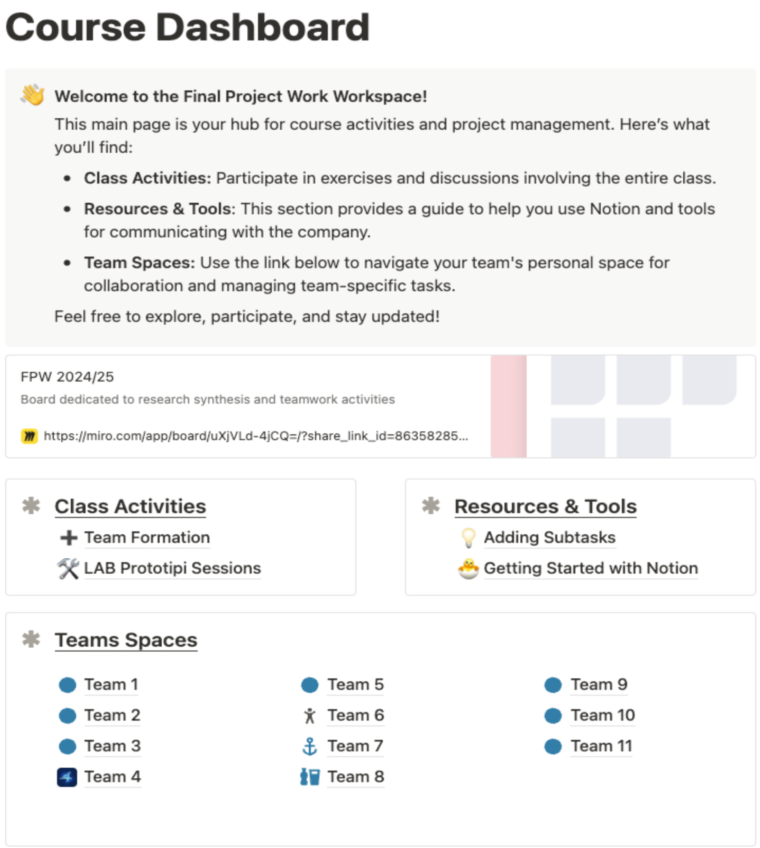


Figure 3.2. Screenshot of the course dashboard.

Course dashboard

The course dashboard (Figure 3.2) is the main entry point to the course – the home page. From here, students can access three key areas: Class Activities, Resources and Tools, and Team Spaces. The Class Activities section includes pages for class-wide collaboration, such as group formation at the course launch or collaborative tasks that do not require specific team divisions (e.g., booking a reverse engineering session in the lab). Notion's database feature proved to be remarkably flexible. For example, a database was created to support team formation by documenting patterns of past collaborations.

This enabled the teaching staff to gain insights into existing group dynamics and to encourage students to explore new collaborative opportunities, without collecting or storing any personally identifiable information.

The Resources and Tools section is a collection of custom help guides (e.g., Getting Started with Notion) and practical resources (e.g., Adding Subtasks) to support students as they navigate the platform. This section is designed to be dynamic and can be updated in response to emerging topics and students' questions or suggestions, providing more space for teaching staff-student communication.

A link to a collaborative Miro board was also integrated into the course dashboard. This board functions as a tool to support the development of a team agreement, wherein students first share individual expectations for teamwork and subsequently collaborate to draft a formal team contract. The team contract establishes shared norms, delineates acceptable and unacceptable behaviours, and assigns roles and responsibilities within each team. Working simultaneously on the same board promotes transparency, mutual learning, and a sense of alignment across all teams.

The last section is populated with the team spaces. These are managed by each team and contain all the information on team collaboration, project management, review feedback, and communications with the partner company.

Team spaces

A team space is a virtual private environment for each team dedicated to teamwork and project management[1]. Each team has a default set of core pages organized into sub-sections (i.e., project management, teamwork & collaboration, reviews grading, and partner company), as per Figure 8.3.

Note 1. A work-in-progress version of the FPW Notion space can be accessed and viewed at the following link: bit.ly/course_dashboard.

The Project Management section includes the design decisions diary (DDD), where teams document discussion topics for meetings with the teaching staff and collect, synthesize, and respond to feedback. At each milestone, the DDD can be exported as a PDF and submitted to account for the team's ability to make decisions, manage process iteration, and interpret feedback constructively and assertively. The second element is the Gantt chart, where teams plan and assign tasks and milestones related to specific modules and deliverables. Notion's Gantt chart view enables the creation of task dependencies and subtasks intuitively and allows individual tasks to be assigned to one or more team members. Two additional pages were included to support collaboration and team alignment (i.e., Team Meetings and Files). The Team Meetings page serves as a log for meeting frequency and meeting notes, so all team members are always aligned. A separate page named Files was also provided, where teams can upload files for safekeeping and progress tracking.

The Team Agreement and private collaborative tools (e.g., Miro board), part of the Teamwork and Collaboration section, represent a central pillar of the overall process. Here, each team declares and agrees on how to face the project collaboratively.

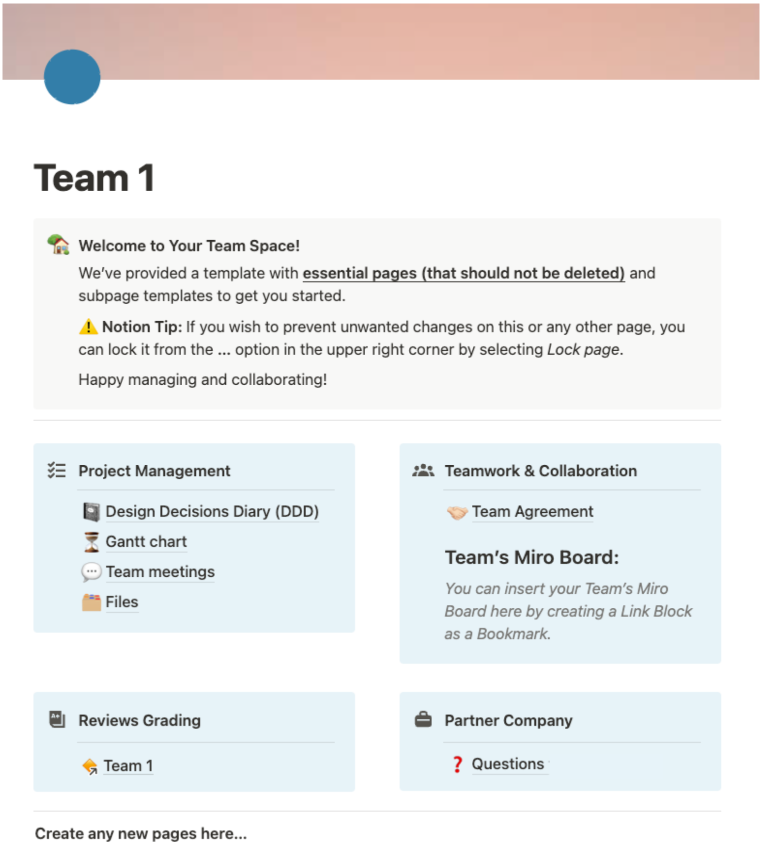


Figure 3.3. Screenshot of Team 1's Space.

The Reviewing and Grading section provides students direct access to monitor their progress based on the teaching staff's qualitative and quantitative review assessments. Students can also immediately see their tendency ups and downs over the semester through a graphical view. At the same time, the teaching staff has access to all teams' performance and can identify the stages in which teams struggle or excel.

Finally, the Partner Company section is a centralized space where students submit questions or technical concerns weekly to be forwarded to the partner company that provides the initial design brief. The teaching staff compiles the submissions and forwards them to company representatives.

The FPW Notion space, encompassing competencies, methods, and tools, is designed as a scaffold or an adaptive and supportive platform for student teams as they develop their project management and collaboration skills. It is not intended to be a compulsory or rigid infrastructure but rather a flexible resource that supports students in discovering what works best for them to navigate project complexity and collaborative learning throughout the design process. The following section explores how each team engaged with the platform and how it influenced their understanding of the collaborative processes in design.

3.3 Engaging with and making sense of collaborative tools

In this part of the chapter, we examine how students engaged with the platform in practice and how they reflected on it. Between September 2024 and January 2025, the 51 students divided into 11 teams engaged with using the FPW Notion as part of the course. The analysis unfolds in two parts. First, we explore how different teams appropriated the Notion environment, identifying four distinct modes of engagement – from immersive use to reluctant uptake – highlighting how teams navigated the same platform in significantly different ways. These modes reflect varying levels of integration, perceived usefulness, and alignment with team workflows. Second, we turn to students' written feedback on the course evaluation to understand how they perceived and internalized the collaborative method by the end of the course. Thematic coding and mapping of their comments show how project management and team collaboration emerged as central concepts, anchoring a broader set of competencies.

3.3.1 Four levels of student engagement

Looking at how student teams used Notion throughout the course reveals four distinct patterns or levels of engagement (i.e., immersive, selective, passive, and reluctant), each reflecting different ways of understanding and applying project management within a collaborative design process.

Immersive teams approached Notion as a fully functional project management environment. They extensively used its features (i.e., tasks, subtasks, deadlines, priorities, assignments, and task dependencies). A few teams went further, creating clear responsibility structures by assigning primary and support roles and consistently keeping track of meetings and shared files. For these groups, the Notion space became a working infrastructure, actively supporting the unfolding of their project work from start to finish.

Instead, *selective* teams made more targeted use of the platform. These teams added what they needed (e.g., a calendar to manage deadlines or a task list to clarify roles) but did not integrate the platform across the whole project. In some cases, they moved parts of their planning to other platforms like Figma or turned to paper-based methods for milestone tracking. In these situations, Notion served more as a temporary scaffold than a core structure. This partial engagement may be related to perceived limitations in the platform itself. One student suggested "considering other tools for the Gantt and task assignment" as "it wasn't very easy to use". Another student shared that the Notion Gantt chart was "not so handy to use" and "a bit overstimulating".

A third set of teams, which we labelled as *passive*, barely engaged with the platform. Their Notion spaces remained almost as the original template, with minimal modification. Some added a calendar or draft notes, while others abandoned the platform early on, suggesting either a lack of interest or a preference for different organizational tools. This low level of engagement resonates with some of the more critical student reflections. One student described project management in the course as "nearly useless" and "just a waste of time", while another argued that "forcing everyone to use Notion didn't seem right or fair". These comments point to a misalignment between the intended scope of the platform and how these students perceived their own needs and working styles. In some cases, the issue extended beyond the platform itself. A student described how "some persons eventually would disappear or just decline responsibility", pointing at deeper challenges in team collaboration. Here, a passive approach to Notion may not reflect a rejection of the platform per se but rather a broader breakdown in collaborative practices.

Finally, the only *reluctant* team used Notion primarily for internal documentation. They uploaded research summaries or scattered notes but barely interacted with the platform's planning or coordination features, focusing solely and superficially on the Gantt chart. In these cases, the space operated more as a passive archive than an active management platform.

These engagement levels highlight the adaptability and versatility of such a platform to meet various needs, workflows, and cognitive structures. At the same time, it reflects how unevenly the tools embedded within the platform are interpreted and taken up. This raises questions on how much structure is needed to make an effective and meaningful management platform across different teams. We discovered that even when starting with a shared baseline framework, the same tools could become essential for some and irrelevant for others. Nevertheless, despite this uneven engagement, many teams developed their own strategies for managing the project and acknowledged the value of integrating project management and collaborative learning within the course curricula.

3.3.2 Making collaboration tangible

To understand how students perceived and internalized the method proposed in the FPW course, we thematically analysed their feedback and mapped the relationships between recurring topics. We gathered input from students through a dedicated Microsoft Form questionnaire, which was distributed immediately after the course, and collected responses from 24 students (approximately 47% of the class). The form included four open-ended questions (Table 3.2) aimed at capturing students' key learnings (i.e., Q1), perceived strengths and weaknesses of the course (i.e., Q2 and Q3), and suggestions for improvement (i.e., Q4).

Q1	What have you learned in this course?
Q2	Which was the thing you liked the most?
Q3	Which was the thing you liked the least?
Q4	Any suggestions for next year?

Table 3.2.
Questions asked to students in the dedicated Microsoft Form distributed by the teaching staff.

We generated a visual map (Figure 3.4) based on the main topics or codes identified in students' responses (Table 3.3). This map illustrates how students interpreted collaboration as a workflow and a learning network, with "effective communication" as a pivotal anchor. Around this central node, three clusters of frequently co-occurring topics emerged: (1) "project management", "managing complexity", and "team collaboration"; (2) "task management" and "time management"; and (3) "progress tracking". "class-wide collaboration" was the only isolated topic addressed independently in students' reflections and was thus not included in the visual map.

In terms of effective communication, several students highlighted how they learnt "to present [their] ideas and thoughts more effectively" and to "better communicate a project". Communication was not limited to interpersonal exchanges, though. It also included documentation and traceability, with one student mentioning the value of "creating documents and design process documentation [...] to have

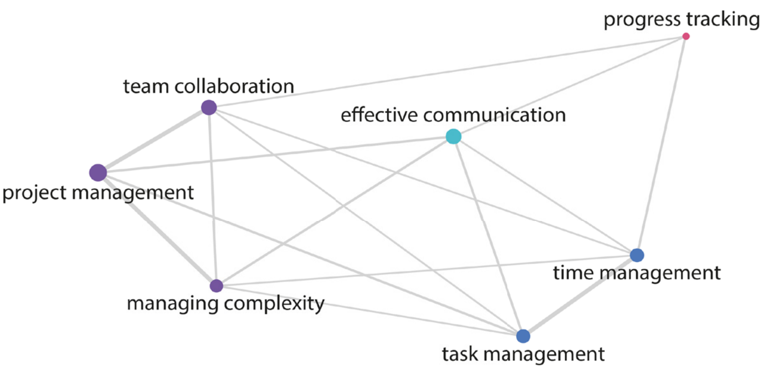


Figure 3.4.
Code relation map of key topics emerging from students' responses. It represents the frequency of concurrent codes in the same response. The size of the dots is directly proportional to the number of responses containing those topics. The thickness of the joining lines is directly proportional to the number of times two connected codes appear in the same response.

a trackable design trajectory". Another described learning to manage review meetings by "writing objectives beforehand, taking notes, and outlining next steps". All these practices consequently contributed to more informed decision-making.

Table 3.3. Code system and code frequency per response to each question.

Code	Q1	Q2	Q3	Q4	Total
Class-wide Collaboration	0	6	1	4	**11**
Effective Communication	4	0	2	1	**7**
Managing Complexity	6	0	0	1	**7**
Professional Approach	2	1	0	0	**3**
Progress Tracking	2	0	0	0	**2**
Project Management	14	2	0	0	**16**
Task Management	5	1	0	2	**8**
Team Collaboration	10	0	3	1	**14**
Time Management	3	0	3	2	**8**
Total	**46**	**10**	**9**	**11**	**76**

A significant number of students identified project management as their main takeaway. They reflected on having learnt "how to better structure, organize, divide, and communicate a project" and how relevant it was to grasp "how to develop in-depth a project of […] technical complexity". Project management was often discussed alongside team collaboration and managing complexity, suggesting that mastering project management tools and methods enabled students to understand the fundamental role of team dynamics in "juggling different disciplines at the same time" and addressing technically demanding tasks. These practices further supported the acquisition of time management and task management competencies. Comments such as "[I learnt] team and time management, especially using Notion, to plan and track progress" or "[I learnt] how to organize the workflow in a precise and well-scheduled way" reinforce how this approach helped shape students' working strategies. Another theme that surfaced from the analysis was progress tracking, which students framed as a method for both "team and time management" and for ensuring accountability and "finding fault" in the design process.

Although class-wide collaboration did not appear in the code relation map, several students described it as one of the course's most distinctive and appreciated aspects. The possibility of exchanging feedback between groups was often mentioned as a valuable learning opportunity – "the idea of exchanging feedback between groups was really interesting" – especially compared to previous experiences. One student praised the class environment by saying that "the atmosphere in the classes with the rest of the classmates was great, and helping each other was fantastic", and another described it as an "environment that permitted the exchange of ideas and opinions".

These clusters of topics reflect a multi-layered understanding of collaborative design projects, from competencies such as time and task management or effective communication to methods like team collaboration, class-wide collaboration and progress tracking. The code relation map helps visualize how students navigated collaboration's strategic, organizational, and interpersonal dimensions, with effective communication competence at the centre. This centrality highlights communication as the underlying structure, enabling students to make informed decisions, coordinate tasks, and collaborate on their projects. These insights suggest that the FPW course did more than familiarize students with project management tools and methods – it facilitated a shift in how students conceptualized collaboration, making it tangible, structured, and transferable.

3.4 Towards a collaborative design education culture

This chapter explored how collaborative learning and project management can be meaningfully integrated into a design project-based course through designing, developing, and testing a low-fidelity prototype of a management platform using Notion. Drawing from and adapting Parsons & MacCallum's (2019) pyramid, we reframed collaborative project-based learning around a hierarchy of competencies, methods, and tools. Based on this reinterpretation, the platform served not only as a digital organization tool but also as a pedagogical environment for making collaboration tangible and transferable. It provided a space for students to engage with the complexities of teamwork in design projects, supporting progress tracking, team and class-wide collaboration, continuous feedback, and direct stakeholder engagement. In doing so, it operationalized the principles of project-based learning while reinforcing key competencies such as communication, time and task management, collaboration, and self-reflection.

Despite uneven engagement, students recognized the platform's value in improving their project management strategies. Feedback analysis indicated that students acknowledged key concepts like team collaboration and project management as essential and actively internalized by many as part of their evolving design practice. The course experience helped shift the perception of collaboration from a requirement to a strategic and professional competence essential for navigating the complexities of real-world design projects.

The prototype also revealed opportunities for improvement. Usability limitations, particularly regarding the Gantt chart, hindered a generalized immersive adoption. Future iterations could explore hybrid integrations with more specialized tools or enhanced personalization to support diverse working styles. In addition, students' selective and passive engagement patterns suggest that a one-size-fits-all solution may not be ideal. Offering more flexible paths of engagement could help better align with team dynamics and organizational preferences.

In conclusion, the design and implementation of the Notion platform proved its potential as a pedagogical environment that does more than support coordination – it can foster a culture of collaboration in design education. Making the tacit dimensions of teamwork and project management visible can encourage students to engage more critically with these processes. Balancing structure with adaptability, the platform becomes a prototype for future models of integrated learning environments, where collaboration is not an add-on but a central, designed experience.

Acknowledgement

We would like to sincerely thank our students, whose active participation and thoughtful feedback have been instrumental in shaping the reflections presented in this chapter and will contribute to improving future teaching practices in the years to come.

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PART 2

Exploring through prototypes

4. Graft-games: investigative prototypes for the cumulative exploration of similarities between craft and the play of videogames

Gemma Potter

4.1 Introduction

This chapter presents an experimental prototyping approach termed *grafting,* developed for directly exploring similarities between craft and the play of videogames. Through two case studies, I will demonstrate the role graft-game prototypes played in the investigation of abstract concepts as part of a non-iterative yet cumulative, participatory process. With the increasing application of gamified approaches across multiple fields including design research, the case studies also reveal the importance of considering embodied actions when designing game-based interventions. The role of embodied skill in the play of videogames has gained increasing attention in recent years (Brock & Fraser, 2018; Brock & Johnson, 2021; Nitsche & Sherman, 2024; Nørgård, 2012; Reeves *et al.*, 2009). Skill, according to Sennett (2008), is "a trained practice" developed by "going over an action again and again" (pp. 37-38), a process through which practices are converted into tacit knowledge. A similar acquisition of skill is required for the playing of videogames with players displaying "remarkable dexterity developed through many hours" (Reeves *et al*., 2009, p. 205). Through gameplay, the players "develop a deep understanding of their material: the game" (Potter, 2022, p. 47). The prototypes discussed here were developed for directly exploring these similarities. The approach builds upon direct engagement with amateur craft practices – including handknitting and macramé – and videogame play – including Mario Kart 8 Deluxe (Nintendo EAD, 2017) – on the Nintendo Switch and Unravel (Coldwood Interactive, 2016) on PC. An investigative designing approach (Durling & Niedderer, 2007) was implemented in which craft activities were directly connected to a digital game through a process which I refer to as grafting (Potter, 2023). I use this term to describe the bringing together of two distinct elements that results in a combined effect greater than the total of the two individual elements. This approach was employed not to simply create an input or output for a digital game – as seen in *craft games* discussed by Sullivan and Smith (2017). Instead, the approach was employed to prototype the bringing together of craft and gaming as an investigative tool for exploring the impact this has on the individual activities.

I adopt the term grafting to describe the act of joining together two distinct items as used in horticulture to describe joining "parts from two or more plants so that they appear to grow as a single plant" (Bilderback *et al*., 2014, para.1). Grafting, as a term, is also found in knitting, otherwise known as *Kitchener Stitch*, used to describe a method of seamlessly joining two pieces of knitting (Gutierrez, n.d.). The approach to grafting here had similar aims, seeking to join craft with gaming via a seamless physical join that creates a conjoined and overlapping experience. The graft-games developed were *not* designed as prototypes for testing solutions to a defined problem but as a method for investigating the impacts of directly connecting craft with gaming. The advantages of this as a prototyping approach included: (a) providing (cumulative) insights into abstract and inarticulable concepts through activating direct interaction at public events and (b) eliminating excessive prototype development through the use of established craft activities and adapting existing digital games. Each of the graft-games developed was showcased at a series of events, with members of the public invited to engage directly with the prototypes.

4.2 Graft-game case studies

4.2.1 Developing *Hazuki Knit*

In developing the graft-games, a particular craft action formed part of the core mechanic so that the act of making remained intact. Although developments in physical computing have created opportunities to “merge crafting activity with electronic and digital game design” (Sullivan & Smith, 2017, p. 38), current commercial technologies are still somewhat limited in terms of capturing the fine-tuned movements of hands in craft. Instead of trying to employ technology to monitor hand movements, it was decided that utilizing the movements of craft tools and machines, to which electronic components such as switches and sensors could be added, would be more straightforward and require less fine-tuning or calibration. Having engaged with hand-knitting previously, and with domestic knitting machines available second-hand, machine knitting was selected for the development of an initial graft-game. Knitting with a domestic machine offered an immediacy in the production of knitted fabric with no requirement for digital technology. Unlike hand-knitting, which can be a slow process, machine knitting is reasonably fast. A flatbed knitting machine, a Brother KH-836 in this case, has over 100 needles that knit a full row of knitting almost simultaneously. This is controlled by moving a knit carriage (by hand) across the bed of needles, producing one row of knitting with each pass.

The graft-games discussed in this chapter were developed in collaboration with an artist-technologist and alternative game developer, James Medd. The first, *Hazuki Knit,* made use of an existing standalone game previously developed by Medd called *Hazuki*. *Hazuki* was designed as an online game “inspired by ‘quick time events’ experienced in video games” (Potter, 2023, p. 851). Quick time events (QTEs) ask players “to respond to events in a gameworld by making specific control inputs, either in a limited time, or to a particular timing” (Tavinor, 2017). Generally appearing within videogame cutscenes, the mechanics of QTEs are separated from the main game narrative but can also be experienced as a core mechanic of games such as *Dance Dance Revoluti*on. *Hazuki Knit* “focuses solely on this playing style utilizing the four arrow keys on a computer keyboard (up, down, left, and right)" (Potter, 2023, p. 851). Players have to press the corresponding key each time a symbol appears on screen. If the wrong key is pressed or the player is not fast enough, the game is over. The goal of the game is to achieve as high a score as possible, with a live score displayed throughout. This existing game, developed by Medd, presented an opportunity as gameplay appeared to reflect the repetitive nature of the concurrent movements in knitting and was thus seen to be compatible with actions of knitting on a knitting machine.

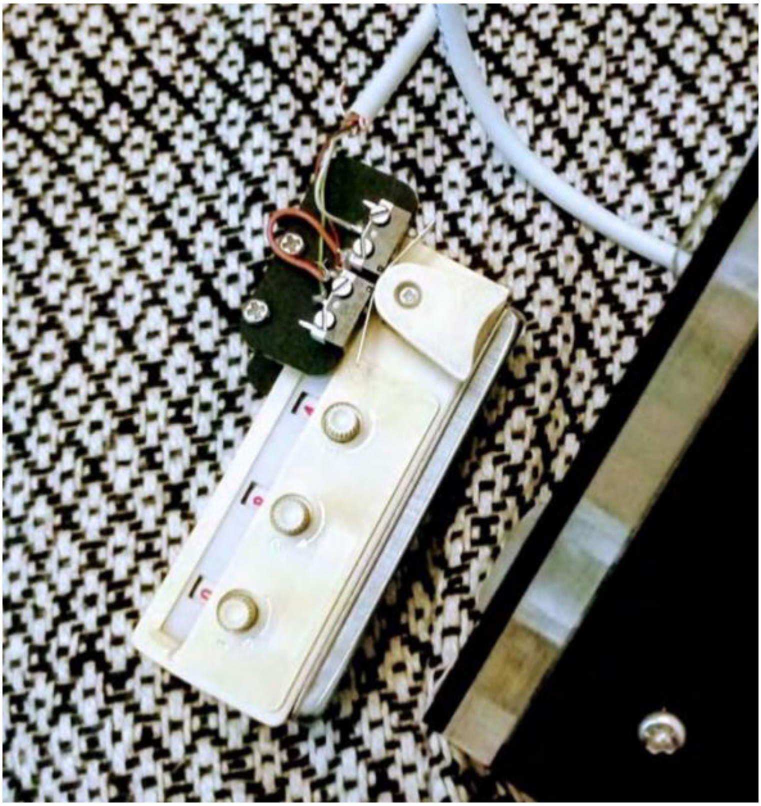
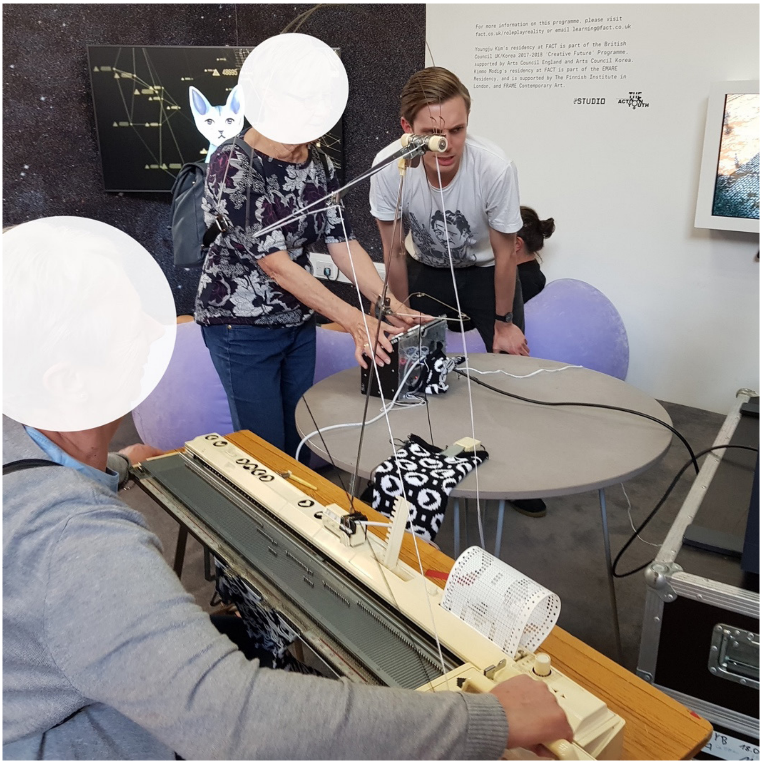


Figure 4.1.
Row counter from the knitting machine with added switches above the carriage trigger.

Having decided upon a knitting machine and an existing digital game, a method of grafting the two together was developed. We set out to capture the action of the carriage moving back and forth across the knitting bed. For experienced machine knitters, this action would generally be done at an optimal pace that responds to yarn type as well as tension and width of the knit fabric being produced. To harness this action, we added two small switches above the row-counter on the knitting machine (Figure 4.1), a common feature on knitting machines that tracks the number of completed rows. The counter does this using a trigger that flicks back and forth as the carriage moves past it in either direction. Adding switches enabled this movement to be integrated into the digital game, determining when the directional prompts would appear on a screen and thus controlling the speed of the game. We created a custom tabletop control panel with four large arcade buttons for the directional arrows. Once combined, *Hazuki Knit* became a two-person experience with one person controlling the knitting machine and the other pressing the buttons on the control panel.

Figure 4.2. Participants interacting with *Hazuki Knit* at an event in Liverpool, UK.



Hazuki Knit was first showcased in May 2018 as part of an event in Liverpool in the Northwest of England (Figure 4.2), followed by two additional events elsewhere in the region in the following 12 months. Both Medd and I facilitated participants' engagement with the graft-game, and observations were recorded in the form of reflective field notes along with video recordings of participants' hands during gameplay. These recordings also captured any remarks, sounds and responses of the participants during gameplay. The data was later analysed using Braun and Clarke's (2006) framework for thematic analysis.

4.2.2 Observations of *Hazuki Knit*

During observations, two forms of gameplay emerged: cooperative and competitive. Cooperative play was led by participants on the knitting machine, with players observed deliberately pausing between rows to give the other player longer to respond to the on-screen prompts. This reduced the risk of *game over*, demonstrating that players were motivated to achieve a high score by working cooperatively. We did not observe any comparable desire in relation to the knit fabric being produced, suggesting that getting a high score was preferred, prioritized even. This may not have been the case if the activity had been framed differently – *Hazuki Knit* was generally presented at these events as a game – perhaps with a finished knitted object defined as a goal for each set of players. Instead, any knitting that was produced was merely a by-product of successive and ongoing gameplay, and as such acted as a collective output produced by all participants.

Competitive gameplay that emerged during observations of *Hazuki Knit* was also led by the player on the knitting machine. As stated by Hunicke *et al.* (2004), competitive games "succeed when the various teams or players in the games are *emotionally invested* in defeating each other" (p. 3). Juuls (2013) argues that this is something that is seen as acceptable, expected even, in the context of games and gameplay. In playing *Hazuki Knit* competitively, deliberate actions by the player on the knitting machine made the game harder for the other player, simply by knitting faster. The increased speed at which prompts would appear on the screen required the other player to press the directional buttons more quickly in response. At the same time, the faster knitting pace resulted in an increased level of noise from the knitting machine which appeared to impose a sense of urgency in the other player. This competitive style of gameplay was generally accompanied by expressions of pleasure and joy from both players. This was even the case when players experienced game over.

Rather than expressing frustration, both players demonstrated what McGonigal (2011) describes as "fun failure" (p. 64). This competitive style of gameplay, however, tended to negatively impact the knitting machine and the quality of the knit fabric being produced. The excessive pace of knitting put the knitting machine at risk of jamming and increased the risk of holes or ladders occurring in the knitted fabric, errors that were less noticed by players focused on the 'fun' of the game. In general, neither the cooperative nor competitive styles of gameplay that emerged appeared to prioritize the production or quality of the knitted fabric. In fact, players tended not to monitor or pay attention to the knitted fabric at all.

4.2.3 Developing *Pocket Racer*

A second graft-game was developed through grafting together another existing digital game with a craft process that used a sewing machine. This second prototype was intended for showcasing at the *Festival of Making* in Blackburn (in the UK), an area with a rich history of textile making and an ongoing manufacturing industry. Inspiration was taken from the working practices found in the manufacture of clothing in the town. Industrial sewing machines are costly and bulky items, often attached to specialized flat-bed tables, which would be difficult to transport to a public-facing event. Instead, a domestic sewing machine, which shares many features with industrial models, was used.

As observations of *Hazuki Knit* had revealed that participants had little awareness or concern over the quality of the knitted fabric being produced, we decided that for the second graft-game, a specific outcome for each participant to complete would be a set goal for each player. Each would be tasked with completing a facsimile of a patch pocket, a common feature on many garments and a manageable activity that could be completed by a large number of participants. The event was expected to have a large number of visitors, which posed a challenge in terms of safety. All sewing machines have a sharp metal sewing needle through which the sewing thread is threaded. When the machine is powered, enacted by the machinist, this needle moves up and down passing through the fabric beneath at a fast pace. This action posed a risk for anyone using it, especially for young children who may have participated – under-18s were not observed as part of the research but were not excluded from the activity. Although instruction could be given to each participant on how to position their hands during sewing in order to remain clear of the needle, this required a cautious approach, which was not ideal for a busy event. Instead, the machine was adapted with the needle removed, and a small felt-tip pen was clamped to the sewing foot. The machine, with the pen attached, would be used to draw around a pocket shape closely replicating a sewing process whilst minimizing safety risks. The use of a felt-tip pen and lack of thread meant that fabric was no longer essential, and a paper template was created, which also simplified the preparation of materials for the event. The template, as shown in Figure 4.3, featured a dashed line in the shape of a pocket (with an opening at the top), representing the desired stitch line with a shaded grey region on both sides of it. The aim for each participant was to sew (draw) as closely as possible to the dotted line and stay within the shaded region. Any pocket sewn outside of the grey region would be rejected, just as inaccurate sewing in a factory setting would not be acceptable in production.

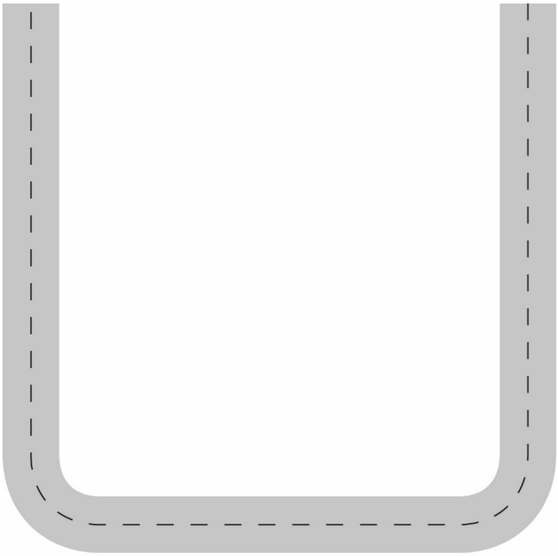


Figure 4.3.
Pocket template used for *Pocket Racer* graft-game.

As with *Hazuki Knit*, the grafting approach in *Pocket Racer* utilized an existing digital game. We wanted to use a game that focused on speed as its core mechanic, to mimic the need for high levels of productivity in garment manufacturing. Medd had previously developed a game called *The Mashing*, inspired by frantic button-mashing required in some arcade games.

> **The game is very straightforward: two teams of up to five players each have a designated button to press. On-screen are two coloured bars that increase in height with every press. Once a team's bar reaches the top of the screen, they win the game. (Medd, 2015, para. 4)**

As discussed, observations of *Hazuki Knit* had revealed that the game aspects had distracted somewhat from the knitting element, resulting in increased errors in the knitted fabric, so it was decided that any visual elements of the digital game would be kept to a minimum. The intention was to allow participants to focus on the sewing machine and the visual progress of the drawn stitch line on the pocket template. The on-screen visual in *The Mashing*, supported by a set of sounds, also communicates progress: a countdown sound at the start of the game; a satisfying *bing* sound that increases incrementally in pitch each time the bar rises; and an end sound when the fastest team's bar reaches the top. These audible feedback elements were adopted alongside the sewing machine, removing the need for an additional on-screen marker of progress. It was intended that this would reduce distraction from the craft output as observed with *Hazuki Knit*. *The Mashing*, in its original format, was a multi-player game with two teams of five. Competitive gameplay observed between players of *Hazuki Knit* was seen to increase the risk of errors in the knitted output. With *Pocket Racer* being inspired by garment production where the quality of output is important, we wanted to remove this additional element of risk, so it was decided that it would be a single-player game, with competition only featuring as a non-synchronous experience.

To connect the sewing machine and the game, a mechanism was required that would enable live tracking of the progress made in sewing around the pocket template. Through setting a standard stitch length, the number of stitches required to complete a full pocket was calculated. To capture the number of stitches completed in real-time, two actions of the sewing machine were considered. As a sewing machine stitches, the sewing needle ordinarily moves up and down, but as the needle in this case was being replaced by a pen, this movement would not occur in the same manner. A second action occurs during sewing, a handwheel at the right-hand side of the sewing machine rotates continually, completing one full rotation for each stitch sewn. A hall effect sensor (which detects the presence and magnitude of a magnetic field) was temporarily mounted to the top of the sewing machine above this handwheel. A small magnet was then attached to the edge of the wheel and, as it turned, the magnet passed the sensor, which in turn sent a signal to an attached Arduino controller (Figure 4.4). The digital game was then customized to look for this signal instead of a button press with the in-game sound triggered when a single stitch is completed. A starting countdown sound was retained from the original game accompanied by an on-screen

Figure 4.4. Participant interacting with *Pocket Racer*, including a sewing machine with a sensor positioned above the handwheel, an external Arduino, and accept/reject buttons.

countdown, and the end sound was triggered when the specified number of stitches (and thus the pocket) were completed. A series of external buttons were connected to *start* the game, alongside an *accept* and a *reject* button that would be pressed by the facilitator when judging the quality of the completed pocket, i.e., if the stitching remained within the grey zone. Once the pocket had been judged, the screen would display the participant's score: the time taken to complete the pocket. The goal of the graft-game was set – to sew around the pocket as fast and as accurately as possible.

4.2.4 Observations of *Pocket Racer*

The graft-game prototype, *Pocket Racer*, was showcased at the *Festival of Making* in the summer of 2019 – a very busy event with over three hundred people engaging with the graft-game over the course of two days. Despite being a single-person game, *Pocket Racer* still retained a competitive element, with the highest score (shortest time taken to complete an accurate pocket) being displayed for visitors to see throughout. Unlike *Hazuki Knit*, the desire to sew the fastest pocket (i.e., to achieve a high score) did not overpower or detract from the desire to sew an accurate pocket.

Participants playing *Pocket Racer* received feedback on their progress during the game both visually, through observing the line being drawn around the pocket shape, and via the audible *bing* sound which increased in pitch with each completed stitch. After each player finished, the drawn line was looked at for closeness to the desired stitch line and deemed either as *accepted* or *rejected*. The decision was made through visual inspection but often involved discussion and agreement with participants themselves. The decision was confirmed verbally to the player and by pressing the *accept* or *reject* button. Players would then wait patiently for their game score to be displayed. This demonstrated that both the game score (speed) and accuracy were valued equally by participants. In *Hazuki Knit*, the game score was seen to be valued but to the detriment of the craft output that, if not carefully monitored during grafted gameplay, would result in flaws in the knitted fabric. *Pocket Racer* was more balanced with visual attention kept on the craft aspect throughout the sewing process. Quality was not consistent, and many participants' pockets were rejected for going outside of the defined border, but participants demonstrated a concern for quality and an awareness of the stitch line going beyond the accepted limit during gameplay. The judging of finished pockets as inaccurate led many participants to want to improve quality, necessitating the processes of repetition linked to the acquisition of skill (Juul, 2013; Sennett, 2008). Within *Pocket Racer*, a rejected pocket was met with expressions of disappointment such as an audible sigh. One participant described their first completed pocket as "off-road driving" and immediately asked if they could try again.

A competitive drive to beat their own score (or someone else's) also appeared to be a strong motivator for some participants. High-score chasing is an aspect dominant in early arcade games and persists today in mobile videogames (Keogh, 2018), a feature which creates no clear endpoint. Juul (2013) defines such games, of which *Pocket Racer* could be categorized, as a game with an improvement goal, the primary goal of which is to get a personal best, a goal which once achieved "is immediately replaced with the goal of beating the new personal best" (p. 85). This was also observed in *Hazuki Knit* often, with the addition of players wanting to swap places in the game, perhaps to feel more in control of the final score. Within observations of *Pocket Racer*, this goal was accompanied by a desire to beat others', as well as their own, scores. Some players directly expressed a desire to do better than their friends, making comments such as "as long as I beat them". This desire to get the top score was also seen to be a stronger motivation than one of self-improvement. It did not, however, overpower the drive for quality output as it did in *Hazuki Knit*, and players seeking to improve their score were also concerned with still achieving an acceptable pocket.

4.3 Consideration of habitual actions

The embodied knowledge of an experienced craftsperson includes the embodiment of tools associated with the skilled activity (Tanaka, 2013) – the pre-reflective body moves to act even before we consciously "think" to do so (Merleau-Ponty, 2012). This was observed in participant interactions with the tools for both craft and game aspects of the *Hazuki Knit* and *Pocket Racer*.

Hazuki Knit was designed with the intention of being accessible for a range of skill levels so that non-gamers and non-crafters could interact with it as well as more experienced players and makers. Accessibility for a variety of skill levels and previous experiences was achieved through the design of a simple control panel with only four large buttons, with the required symbols, reflective of an arcade game. Accounting for habitual tool use and actions in gaming, we chose deliberately not to use a hand-held game controller as these tend to be specific to certain game consoles (Parisi, 2009) and thus potentially habitual to regular users of each console. Many existing console controllers also have a complex array of buttons and thumb-sticks that may have been excessive for non-gamers. It was, therefore, decided that a custom control panel would be most suitable for a wide range of skills and experiences.

Similarly, a knitting machine has many possible functions that an experienced knitter may utilize. For example, knitted fabric panels can be shaped by adding or reducing the number of active needles across the width of the knit bed to shape panels for a garment. Patterned stitches can be created by manually reversing stitches or adding in additional colours. For *Hazuki Knit*, we deliberately chose not to complicate the functionality of knitting by using different stitch patterns or attempting to shape the knitted fabric being produced. Instead, the knitting machine was set up within the graft-game to knit a consistent width in plain stitch which would allow each participant to only need to move the carriage back and forth to knit successive rows. Additionally, casting off knitted fabric and casting on anew is a time-consuming process, so we decided to knit a continuous length of fabric during events, with every person continuing to knit the same fabric piece. Very few (if any) participants confirmed that they had used a knitting machine before, although some recalled older family members having owned one. The handle of the knit carriage appeared to be very approachable for participants, with players instinctively placing their dominant hand around the handle (Figure 4.5). In general, it did not take long for participants controlling the knitting machine to get into the rhythm and settle into a standard position of holding the carriage handle with their 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. As a result, the properties and the method for playing the grafted game were accessible for a wide range of player experiences, and it did not take participants more than one round of the graft-game to grasp the basics of what was required in order to play.

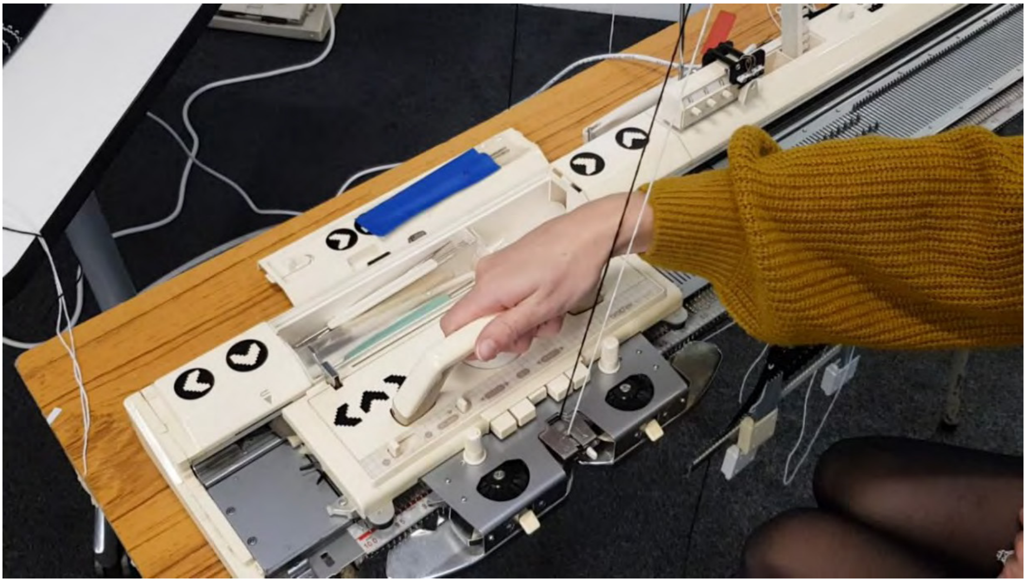


Figure 4.5. Participant's hand moving the carriage of the knitting machine in *Hazuki Knit*.

Experienced machinists (of which there were many), approaching the sewing machine of *Pocket Racer,* acted with the embodied actions associated with their previous experience. This included the body acting based on the experience of using their own, or another more familiar sewing machine. This "knowledge of familiarity" (Merleau-Ponty, 2012, p. 145) suggests that despite being made aware of the machine set up being different (with the sewing needle replaced with a felt tip pen), the body "knew" to act at the sewing machine based on the embodied knowledge that had been developed through repeated bodily practice working with a familiar machine with a sewing needle in place. Participants with embodied knowledge of working with a more familiar sewing machine were not easily able to adjust their bodily actions to the machine with the repositioned felt-tip pen.

Players with previous experience also tended to have additional questions, often seeking to familiarize themselves with any specific technique required for the activity and that particular machine. For example, one player asked, "Have you dropped the feed-dogs? I just want to know what I'm working with". Some participants also expressed a preference for the side of the pocket they wished to start sewing from, aware that it would impact how they turned the paper at the pocket corners. Other participants who had previously used a sewing machine tended to misalign the pocket template at the start, due to their previously embodied actions. A sewing needle would usually be positioned in the centre of the presser foot. For this activity, the desired stitch line needed to be positioned slightly to the right of the presser foot where the tip of the pen was positioned. Those with existing skills who misaligned the pocket demonstrated their habitual practices and embodied familiarity (Merleau-Ponty, 2012) aligning to the foot rather than the pen. This suggests that habitual actions should be accounted for in the development of any future interventions, as stumbling over these actions could lead to undesirable errors.

4.4 Conclusion

Through case studies of two graft-games I have presented *grafting* as an approach to prototyping that enables the enactment and further exploration of theoretical similarities between the skilled practices of craft and videogame play. The prototype graft-games, *Hazuki Knit* and *Pocket Racer,* were developed as part of an ongoing investigation through which observations of participant interactions informed subsequent development. Cumulative insights obtained through the successive prototypes showcased at multiple events enabled the direct observation of conjoined experiences that, unlike traditional modes of prototyping, were not iterative in nature or aimed at producing a refined end product. Collaboration with artist-technologist James Medd and incorporating existing standalone digital games into the grafted games was vital to this approach. These independent, non-commercial digital games, combined with Medd's knowledge and skill set, enabled the prototypes to be developed at a relatively rapid speed using easily accessible components. As set out at the beginning, with the increasing application of gamification within the field of design research and design more broadly, the case studies also reveal the need to consider the implications for embodied and habitual actions for broad useability when incorporating or applying game elements to other skilled processes.

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5. Experiential substance: tactile translations using digital materials

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5.1 Introduction

This research investigates how textiles can be designed and experienced across both digital and physical realms, using digital materials as a key player in the prototyping process enabling the evolution and translation of sensory qualities into concrete form. While textile-design computer-aided design (CAD) programs provide a high-fidelity preview of the design, they lack the ability to convey the sensory and experiential qualities of the resulting fabric, including how fabrics interact with the body through touch, motion, sound, or over time. This gap inspired multiple prototypes that bridge traditional textile techniques and state-of-the-art 3D digital workflows that show promise as dynamic tools for ideation, iteration, and sensory translation.

Our work in the Virtual Textiles Research Group (VTRG) at the Rhode Island School of Design (RISD) leverages deep expertise in designing and fabricating complex textiles to understand how to create richer multisensory experiences in both digital and physical settings. Central to this work are the following guiding questions: How can the tactile experiences of textiles be communicated in a virtual/immaterial setting (without feel)? How can we transfer experiential knowledge of an existing fabric from one mode (e.g., tactile) to another mode (e.g., visual)? How can designers translate speculative concepts for sensory textiles into concrete prototypes? To address these questions, we developed a methodology that foregrounds sensory qualities in material prototyping. The process begins with a "generalized swatch", a conceptual prompt that includes text-based descriptors which directly describe material experience at the outset of the design process. Rather than starting with colourways or fibre choice, this prototype supports the use of words like "crunchy", "staticky", or "buzz" which suggest affective and tactile cues. Further prototypes take the form of a fabricated textile or a procedurally-generated digital material, both of which actualize described traits into physical or virtual form. Two complementary workflows support this process. In the physical-first approach, descriptors that imply textile familiarity lead to the selection of materials and fabrication techniques; 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 when addressing senses beyond the visual. In the digital-first workflow, descriptors that lean toward the uncanny or immaterial are approached through digital material capture and procedural modelling, using tools like HP Z Captis and Adobe Substance 3D Designer. The goal was rarely to come up with a digital twin, but to generate new input for physical translation, forming a cyclical process of material transformation.

Across these methods and tools in our research, we treat prototypes not as endpoints but as evolving expressions of sensory potential. The interconnected formats of our prototypes challenge the conventional assumption of what a textile swatch is, expanding it into a generative format that can accommodate changes in time, scale, and medium. This body of research supports the creative process by opening up the design space to exploration and improvisation, broadening possibilities for new material designs and experiences.

5.2 Background and precedent work

This research builds on a growing body of work that understands materials not as fixed entities but as evolving, experiential systems shaped through interaction, perception, and transformation. Our methodology draws from the field of materials experience, which considers perception, interaction and affect as central to understanding and designing materials (Giaccardi & Karana, 2015). Rather than evaluating materials through static or quantifiable properties alone, this approach engages with how materials are encountered sensorially and their meanings evolve over time and in context. Multisensory frameworks like the expressive-sensorial atlas (Rognoli, 2010), experience map (Camere *et al.*, 2018), and experiential characterization toolkit (Camere & Karana, 2018) have shaped how we articulate and prototype sensory qualities. Their insights on how sensory contradictions – a material that is hard yet soft, for instance – can evoke emotional and surprising responses helped us structure early design prompts. Traditional material mapping often uses binary scales such as stiff/flexible, warm/cold, light/heavy, and rough/smooth, yet materials that defy these binaries often prompt richer, more layered interpretations (Veelaert *et al.*, 2020). This insight is especially relevant to our work developing generative methods for digital-material-making based on textile sensation and haptics. In contrast to the conventional approach embraced by current state-of-the-art creators of digital textiles, which promotes “digital-twinning” in the form of recreating physical fabrics in a photorealistic way, our approach embraces Edelkoort’s (2012) notion of “super tactility” as well as Petreca’s (2017) assertion that a virtual textile need not recreate physical fabric, but rather can balance realistic qualities with the “imaginary and the emotional” (p. 201). In this view, the goal is not replication but transformation.

That materials can be understood as active participants in design also underpins our work. Karana *et al.* (2019) argue that emerging materials – biological, responsive, computational – demand new design models in which materials are not merely shaped by the designer, but co-construct meaning and experience. We apply this in the digital context by viewing procedural design tools (like Adobe Substance 3D

Designer) and procedural materials as generative systems capable of variation, expressiveness, and growth. *Feeling Fabrics* (Meiklejohn *et al.*, 2023) was the first digital material collection that our group created using procedural iteration to prototype sensory experiences. The way that we define what constitutes a prototype is grounded in methods that foreground the temporal behaviours of materials. In textile design, the swatch is a small sample that functions as a "promise and a possibility" (Igoe, 2020, p. 80), and yet in its conventional form represents a finished design, rather than a prototype. The notion of a "generalized swatch" builds on an understanding of material experience as dynamic and emergent, shaped not only by fixed properties but by interactions and transformations. Material samples that change over time, such as mycelium-based composites (Parisi *et al.*, 2016) and textiles that respond to environmental conditions (Talman, 2018), offer additional examples of how temporality can be embedded into material design.

Throughout, our research methods draw upon precedents that prioritize process, improvisation, and embodied feedback. Frameworks such as experience prototyping (Buchenau & Suri, 2000), experimentation as improvisation (Douglas & Gulari, 2015), and material tinkering (Parisi & Rognoli, 2017; Rognoli & Parisi, 2020) embrace the unexpected and the sensorial as productive design tools. Hands-on material exploration played a central role in the early stages of our research, referencing Autonomous Sensory Meridian Response (ASMR), "a relaxing, tingling sensation in the head and neck" (Klefeker *et al.*, 2020), as design inspiration and the idea that unstructured play can yield valuable insights. Meaningful tactile experiences often arise when the designer relinquishes control and allows materials to lead (Aktaș & Groth, 2020; Cary, 2013). This ethos echoes the influential textile designer Anni Albers' advocacy for "active play" as a way of reviving tactile sensibility (Albers *et al.*, 2017) and continues through present-day material activism (Rognoli & Ayala Garcia, 2018) where temporality becomes a form of engagement, not just change.

5.3 Methodology

5.3.1 Capturing textile sensation and haptics

Our methodology begins with tactile exploration, manipulating textile samples through a range of interactions, such as stretching, folding, and compressing, positioning the textile as an object of investigative play.

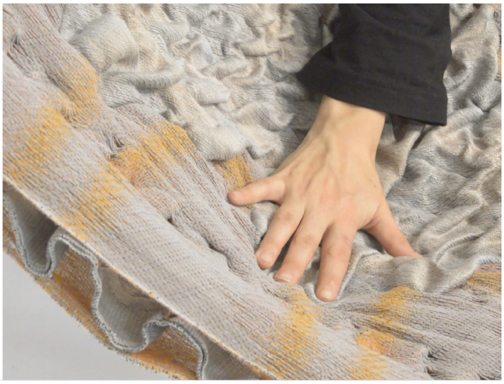

Figure 5.1. Stills from video documentation of interactions with complex woven textiles.

These interactions (Figure 5.1) revealed complex traits such as rebound, friction, structural memory, and even the possibility of transformation under heat or tension. These experiential phenomena, largely absent in static captures, prompted us to develop new ways of capturing material impressions at the outset of the design process.

An early experiment consisted of generative exercises translating sensory impressions across media. One team member would begin by describing a tactile or affective experience using words such as “crackling tension” or “velvety compression”, which the next participant would interpret visually as an abstract image. This chain of translation illuminated not only individual interpretations but also the shared connotations and sensory associations embedded in particular words and sounds. The textile industry often relies on metaphors and similes, using terms such as “peachy”, “sandy”, or “soapy” to describe a fabric’s handfeel. Even non-textile materials are often described using textile-derived words like “silky” and “fluffy”, underscoring how language bridges perception and experience. Among the linguistic strategies for capturing sensorially rich materials were terms such as “buzz”, “crinkle”, and “thump”, which suggested a way of translating sensory experiences synaesthetically. We propose that materials, like words, can be onomatopoetic: their appearance, sound, and texture forming a cohesive expression (like smooth, lustrous silk) or a contradictory one (like a quilted fabric that is bulky yet lightweight). These perceptual contradictions can be especially valuable in prototyping, as they invite surprise, curiosity and heightened emotional response.

This iterative process also revealed a conceptual proximity to text-to-image generative AI tools, which similarly attempt to visualize abstract prompts. While we acknowledge the utility of these systems in rapid ideation and visualization, our approach did not make use of these tools, diverging in its emphasis on inviting human interpretation. Rather than positioning the output as a completed synthesized solution, as traditional swatches or the outputs of AI prompts do, our process treats the initial prompt as a starting point. The designer, drawing on their own individual sensibilities, cultural contexts, and references, actively shapes the translation.

5.3.2 Building a collection of multisensory materials

These generative exercises led to the formalization of the prototype we call the "generalized swatch". These descriptive clusters of text and images form the boundary of what the material could be, serving as speculative prompts. The generalized swatch retains its value as a prototype through its capacity to evolve; the designer can add to it through additional media to reinforce spatial, formal, or gestural qualities. As textile designers, we find that drawing from non-textile sources, such as natural surfaces, patterns in motion, or unfamiliar forms, prevents premature narrowing of possibilities based on colour, fibre or known textile references.

As the designer translates the generalized swatch into material form, it serves as both guide and provocation, open to reinterpretation and refinement. The materials featured in the *Feeling Fabrics* collection (Figure 5.2) demonstrate this translation across both digital and physical domains. Each began as a generalized swatch, and then developed as tangible prototypes using one of two complementary workflows: (a) a physical-first workflow, in which the generalized swatch guides selection of raw materials (yarn and fibre) and fabrication techniques (mainly knitting and weaving) in the creation

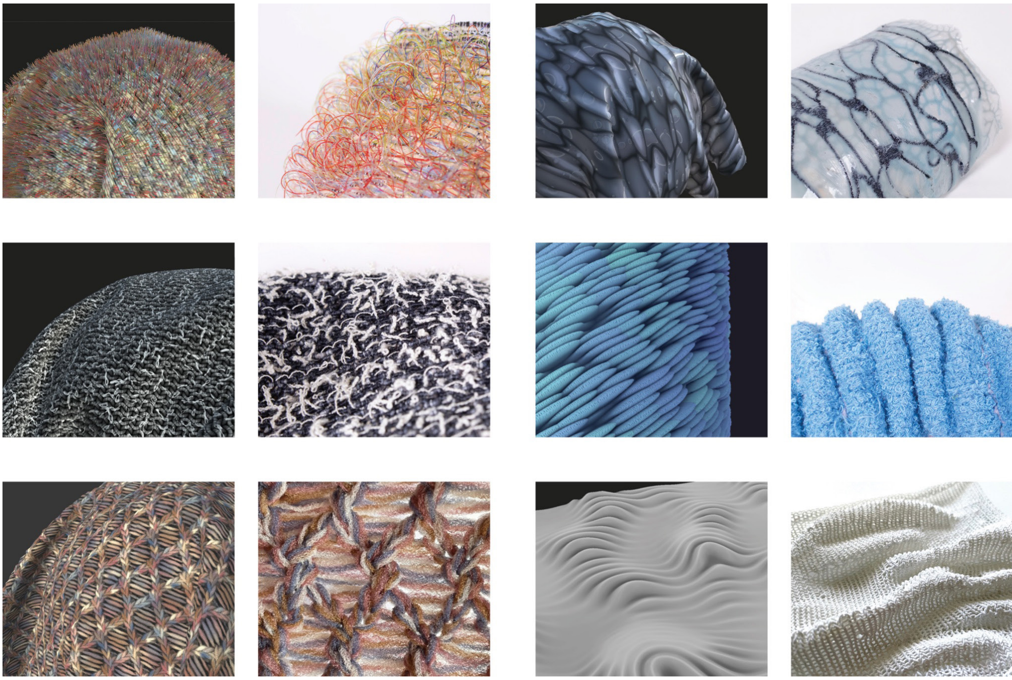

Figure 5.2. Selections from the *Feeling Fabrics* collection of materials, developed using this methodology. For each material design, both a digital prototype (left) and a physical textile (right) were created, in some cases using a digital-first approach and in other cases a physical-first approach.

of a physical sample, and (b) a digital-first workflow that bypasses fabrication constraints, distilling the text- and image-based prompt into a procedural material with flexible parameters. Adobe Substance 3D Designer, a program for creating physically-based rendering (PBR) materials, was our primary tool for digital material development. We employed these workflows in parallel to build a collection of sensorially rich textile materials.

5.3.3 Material creation workflows

At this stage in developing a collection of materials, each design concept was represented by a generalized swatch. To proceed to the material creation stage, we identified candidates for the physical-first and digital-first workflows based on certain criteria of the generalized swatches themselves. Descriptive terms evocative of specific textile techniques were a strong signal that a material could be represented well through conventional textile prototyping. Words like “stiff”, “scrubby”, and “prickly” stood out to us as textile designers: they brought to mind familiar fabrics and objects, like coarse floor mats or abrasive towels. What these fabrics have in common are constructions that include a base layer and a secondary set of short, rigid fibres protruding from it at perpendicular angles, resulting in a scratchy sensation. These implicit connections, informed by both general experience with materials and specialized knowledge about their composition, led us toward a physical prototyping technique (Figure 5.3). Loop-pile knitting, which deposits small segments of a supplementary yarn across a jersey-knitted base, results in a small-scale, randomly distributed texture. This effect can be amplified with strategic material choices; in this case, high-twist linen yarn achieved the desired scratchy effect, coiling into small, dense knots when released from tension. As one of the "onomatopoetic" designs we developed, in which material properties across multiple senses are closely matched, this material had small-scale, high-information visual pattern and texture. We used a black-and-white speckled yarn for the base fabric to emphasize this alignment. Even though the yarn itself is a smooth mercerized cotton, its high-contrast and high-frequency colour changes create a staticky effect that can be perceived just by looking at the fabric. This effect is then confirmed by touching the fabric, a cohesive material experience.

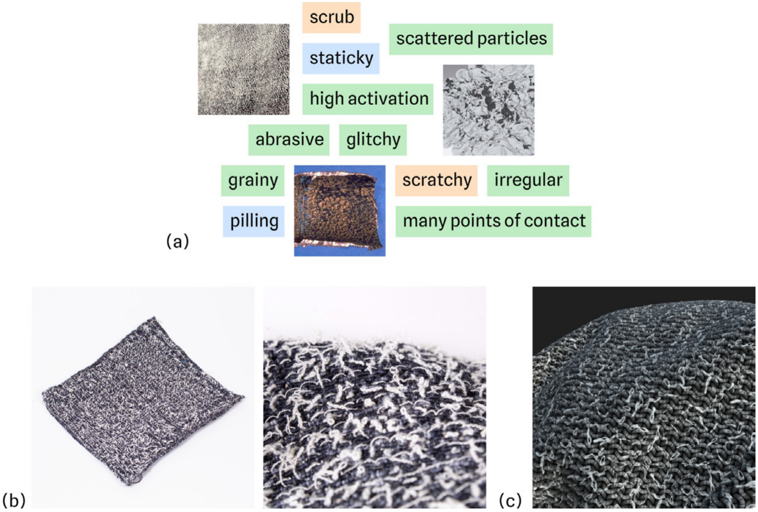

Figure 5.3.
The generalized swatch (a) informs the knitted prototype (b), which is then used as a reference material to develop a digital material in Adobe Substance 3D Designer (c).

When we, as designers, make the logical leap from sensory descriptions to fabrication methods, we initiate a shift from generality to specificity. The generalized swatch, even when it evokes certain textile techniques, still represents a broad space of possibilities; to realize it as a singular material is an act of filling in the blanks that may yield different results for each individual. Next, we assess the physical swatch for the sensory qualities expressed in the initial generalized swatch: does its material experience include these specific traits, and are they subtle or amplified? These observations become part of a feedback loop when creating a digital material. The physical swatch serves as a visual and tactile reference object, which may be followed literally to create a "digital twin". Rather than relying on imagination to sculpt the shape of knitted stitches and twisted yarn loops, the designer can model them from direct observation, embedding a higher level of realism in the material. Unlike typical use cases for PBR material design software, realism in and of itself is not our goal. Instead, it is a reasonable way to ensure that the digital material evokes the same sensory qualities as its physical precedent. Parameters of a fabric's construction, like the gaps of air between yarns and the way fibres are compressed, are integral to how it looks, sounds, feels, and moves. Specificity (e.g., "this material looks sandy; squeezing it in my hands would give me a prickly sensation like pins and needles") and robustness (e.g., "the fabric has so many tiny bumps; it would be extremely scratchy to wear") are possible with this direct modelling approach. The designer may also choose to diverge from the reference swatch, proposing an alternative way of achieving the same sensory experience. Individually manipulating the material's channels in Adobe Substance 3D Designer, such as the normal map, base colour, and reflectivity, can result in a digital material that departs from reality yet still satisfies the initial prompt. Crucially, the physical-first workflow leverages the information contained in the physical swatch regardless of whether it is reproduced or reimagined in the digital swatch. In both cases, it is an equally valuable interstitial prototype.

For materials whose haptic interest is derived not from textile structure but from more abstract descriptors and imagery, a different approach is needed. In the *Feeling Fabrics* case study, these included instances where the generalized swatch contained contradictory pairings of terms, such as "fluid/fractured", that are rooted in physical implausibility. We characterized these materials as digital-first, in part because of their lack of connection to the physical world. They also contained references to biological phenomena or synthetic materiality, which are well represented by the unique feature set of digital material creation. The absence of fabrication constraints in this workflow allowed us to realize these slick, otherworldly textures and patterns. Because PBR represents the material as a thin shell, rather than a three-dimensional model with internal structure, it is inherently illusory. This was not a limitation in our design process; rather, it encouraged further improvisation, such as tuning parameters past the point of realism to make the implied sensory qualities more extreme. The resulting digital materials were speculative yet convincing, leveraging the high fidelity and quick iteration of procedural material design.

One of the materials we selected for the digital-first workflow had references to tensioned, gelatinous materials, suggesting something spontaneously formed rather than handmade. We began by sketching the network of nodes, and thus the underlying logic, of how such a material could be generated. A branching network based on cellular growth patterns formed the base, and a smooth material with low opacity and high reflectivity suggested a membrane or soap film spanning between the branches. Additional layers were applied selectively, based on material reasoning: an air bubble pattern was overlaid onto only the translucent film sections to suggest a rubbery viscosity. This approach enabled us to design a sensorially complex material from an open-ended prompt, relying on free association and material intuition. In an inversion of the physical-first workflow, the digital material was then used as a reference to inform the physical material. The procedural design process exposes options that may not be evident in textile prototyping; materials that originate in digital space can thus inform unconventional methods and raw material selection. In this instance, we developed a hybrid embroidery-casting technique, in which we stitched a piece of dimensional lace and then poured a thin layer of liquid silicone into its negative spaces. This created a stretchy, shiny webbed material that closely matched its digital counterpart. Notably, the vector file for digital embroidery was extracted directly from the node graph in Adobe Substance 3D Designer, a practical feature of this workflow. However, we propose that the most significant impact of designing digital-first materials is the ability to defer decisions about materials and methods to later in the prototyping process, allowing them to be shaped by material qualities rather than shaping the material itself.

5.3.4 Temporal qualities of material prototypes

The parametric nature of digital materials in *Feeling Fabrics* allowed us to explore a wide range of possible expressions within a single material concept, much like the "sample blanket" in textile production. By exposing variables such as pleat depth, pattern density, or colour noise in Adobe Substance 3D Designer, we could animate transitions across multiple states. Some animations simulated real-world deformation, as in the expansion and contraction of a pleated textile, while others suggested a broader space of possibilities, like a material flickering or pulsating between configurations that challenge physical constraints. Arranging the resulting variations into a temporal form allowed us to express the material potential of each generalized swatch as a range.

This approach to material variability lays the groundwork for our next case study, *Phases of Transition*, which explores how textural and structural information transforms across digital and tangible mediums. Rather than treat textiles as static artefacts in fixed states, we frame them as dynamic prototypes that oscillate across states of materiality, perception, and experience. These transitions – temporal, gestural, optical – carry embedded knowledge of movement and making, yet such information is often tacit, accessible only to the user or maker. Typical representations of material swatches or scanned surfaces tend to compress this information, flattening or concealing the variety and complexity of inputs, factors, and intangible components.

To resist premature constraint and cultivate generative freedom in our material design workflow, we utilize emerging technologies such as the HP Z Captis, a state-of-the-art digital material capture system, in combination with Adobe Substance 3D Designer. Material maps are captured from physical material samples, manipulated procedurally to explore alternative modes of material experience, then recomposed into physical temporal forms. The initial capture highlighting textural, structural, and optical qualities set the stage for controlled manipulations of tactile and temporal parameters, allowing us to dissect and expand these qualities in digital formats. These procedural edits (Figure 5.4) became instructive assets for tactile, temporal, luminous, and spatial conditions to inform and generate new material-making outputs. This also gave us the opportunity to highlight various technical and experiential properties that are typically not communicated by standard material representations.

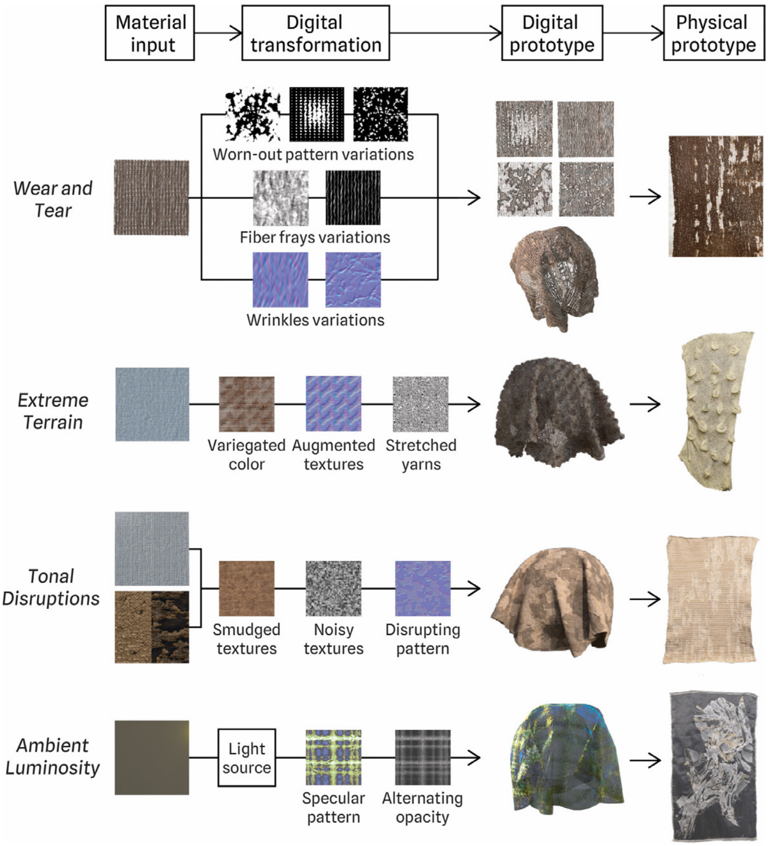

Figure 5.4. Diagram of processes utilized in *Phases of Transition* to develop temporal variations of digital materials.

5.3.5 Prototyping *Phases of Transition*

This case study features four key transformations – *Extreme Terrain*, *Wear and Tear*, *Tonal Disruptions*, and *Ambient Luminosity* (Figure 5.5). Each began with a conceptual inquiry into the abstracted qualities of textile materiality such as topography, aging, movement, light and shadow. Guided by these concepts, the input material was virtually re-shaped and translated into a physical prototype using fabrication strategies such as resist-dyeing, devoré (burn-out), felting, silkscreen printing, and embroidery. Each aimed to materialize qualities often hidden or overlooked in a textile through selective amplification using digital manipulation of the material maps. We particularly explored the aforementioned textile finishing techniques among others, as they can be applied and layered in transitional states, thereby expanding the boundaries of a textile. The physical prototyping process combines parametrically generated assets with the makers' hands-on manipulation, which aims to maintain the intuitive and expressive nature of textile crafts.

Wear and Tear sought to highlight the influence of time and how aging and erosion might be visualized as a continuum. The digital workflow allowed for a sliding scale that could visualize progressive fraying and breakdown, encompassing momentary states that highlight the memory and use of a textile over time, as well as reveal the delicacy of its structural composition in its aging state. In Figure 5.4, we specified three key textural components to convey the sensory qualities of wear and tear: worn-out patterns, fibre frays, and wrinkles. These components can be combined to produce a large number of variations, enabling the speculative exploration of temporal materiality as it emerges through the aging textile. One pattern developed through this workflow was subsequently translated physically using devoré: an acid-paste silkscreened onto bespoke fabric that later dissolved the cellulose yarns that were inlaid within thin, subtle polyester strands, leaving a structure that appears partially eroded yet remains intact.

In *Extreme Terrain*, we explored accumulative materiality that emerges through building up diversified textures. Using procedural modelling, we layered parametrically generated patterns onto a digital textile, producing dynamic topographical and chromatic shifts. These exaggerated variations were designed to prototype yarn-level response to changes in the surface landscape. The digital output then informed the creation of a flat rectangular knitted panel and subsequently shaped with the heat Shibori technique. The process expanded the textile's dimensionality and surface articulation, translating the digitally modelled transformations into a materially expressive physical form.

Tonal Disruptions focused on gestural shifts and tonal variance in surface directionality. These qualities are difficult to capture with static representations, particularly in fabrics with pile, fur, or flexibly attached components like sequins. We designed a digital filter that stochastically activates movement in virtual perceptual formats to convey a smudged gesture. These tactile disruptions were reinterpreted physically through textile techniques such as selective felting and silkscreen printing. We finalized a physical prototype with overlaid expandable foam compound silkscreened on top of a piece of felted knitted wool.

Ambient Luminosity emphasized dynamic optical effects produced by varying degrees of shadow and sheen. These ephemeral optical phenomena were modelled procedurally through patterns that were sequenced to imbue specular and lucid qualities in dynamic light sources. These, in turn, were translated into physical form using digital embroidery with matte and sheen transitions on mesh substrates. The result was a textile that changed appearance in motion and light.

Throughout this process, the interplay between digital capture, procedural transformation, and physical realization established a feedback loop that shaped both form and understanding. This cyclical framework not only produced new material forms but also surfaced latent forms of material knowledge – those that emerge through craft, process variation, and embodied intuition. Rather than aiming for a photorealistic twin, our use of digital materials foregrounds bespoke tactile experience as a primary driver of design decisions. As these procedural digital materials are re-materialized into physical artefacts, they reveal nuanced relationships between digital parameters and traditional textile techniques, allowing us to prototype through phases of accumulation and transition. This approach proposes an alternative approach to textiles that reframes the techniques involved in the making process as parametric modules in dynamic entanglement with each other. These parametric modules are not operated as fixed or terminal states but generative sources that drive the creative process and knowledge reproduction.

As showcased in Figure 5.5, these four panels were designed to be a continuous narrative, allowing them to reveal and obscure one another. Each piece captured a phase of transformation, and when combined, offered a snapshot of material evolution as layered, contingent, and unfinished. These digital tools, when coupled with craft expertise, provide new methods for transferring information and materiality. Through abstraction and recontextualization, we generated not only visual and tactile outcomes but experiential substances: provisional, evolving material states that foreground transformation itself as a core design value. By emphasizing that there is no finished state or constant of a textile, they open pathways for future reinterpretation and transferable substances.

Figure 5.5.
Top: *Phases of Transition* physical textiles displayed together as a material evolution; Bottom: various hands-on and digital textiles techniques used during the physicalization process.

5.4 Conclusion

Our research positions the act of prototyping as a site of experiential inquiry, an approach that redefines how material ideas are initiated, developed and communicated. By replacing the conventional swatch with the "generalized swatch", we offer a flexible framework that captures the perceptual and affective dimensions of materiality. This reverses the typical material-selection processes, enabling designers to develop sensorially complex materials. At the heart of our research is the use of digital materials, not as representations of existing fabrics, but as generative tools within a sensory design framework. Most textile CAD programs prioritize visual accuracy and high-fidelity surface rendering over the sensory or temporal aspects of materials in early design stages. Through the case studies of *Feeling Fabrics* and *Phases of Transition* projects, we leverage the rapid improvements in digital material creation and capture to apply design methods that address sensory qualities in digital space, allowing designers to conceptualize not only how materials will appear, but how they might feel, react, or evolve. Moreover, the procedural workflows highlighted how materials might respond to environmental conditions or user interaction, underscoring their capacity to carry meaning through transformation.

Future steps for this work include assembling a library of digital and physical textile samples. Such a collection would allow comparative studies of sensory translation – how an initial prompt becomes visualized, materialized, and interpreted. Collecting descriptive feedback from outside users would allow us to assess which experiential traits persist or shift across formats, closing the loop on our design process and indicating more precise, powerful, or favourable conditions of material interaction. Unlike automated generative systems that interpret input through large-scale training models, our methodology foregrounds human authorship and intentional synthesis. Designers are responsible for crafting and synthesizing inputs to create a novel material idea. Though more labour-intensive, this approach fosters creativity and deeply personal forms of material expression. It also builds sensory literacy, strengthening the designer's ability to anticipate and communicate affective dimensions of the work.

There is also potential to deepen the role of the prototype in immaterial settings. Audio or interactive movement behaviour could supplement visual textures to convey how a material might behave in settings where the tactile aspect is missing. This is particularly relevant in immersive or screen-based contexts, where the absence of touch limits sensory feedback. There are streamlined software pipelines for bringing digital materials into 3D modelling, gaming, and VR environments, extending the capacity of digital materials to act not just as a visual surface, but as complex sensory systems that anticipate real-world interaction. Through this work, we advocate for a broader understanding of prototyping in textile design, one that treats the prototype as an evolving site of material imagination.

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6. Slow prototyping in biodesign: designing with the living in hybrid laboratories

Francesco Cianfano, Tommaso Celli, Marco Marseglia, Valentina Rognoli

6.1 Introduction

Prototyping has long been recognized as a fundamental part of the design process for validating, exploring, and understanding ideas in context and iterating them. As demonstrated by Buchanan (1992), Cross (2006) and Lim *et al.* (2008), prototypes serve as epistemic and practical tools, giving tangible form to abstract concepts and enabling designers to think through making. Historically, designers have used prototypes to validate their ideas and to understand, test, develop, and refine them over time. The prototype is a crucial step in bringing design thinking to life. It enables abstract concepts to be translated into tangible realities, allowing possible solutions to be explored through the process of creation. This practice is essential and irreplaceable and will continue to be so (Interaction Design Foundation, n.d.).

However, as the discipline has evolved, the design scope has expanded to include the design of materials themselves, moving beyond the mere shaping of artefacts. In this expanded field, prototyping is no longer confined to exploring the form or function of artefacts; it also increasingly engages with their material qualities. Designers have demonstrated their ability to develop material prototypes to investigate not only technical properties but also sensorial, aesthetic, and expressive potential – in other words, "material experience" (Karana, Pedgley, *et al*., 2014; Karana, Pedgley, *et al*., 2015; Pedgley *et al*., 2021). These practices enable the discovery of new applications and stimulate speculative thinking, positioning materials as active agents in the ideation process.

This evolution of material experimentation is deeply rooted in the DIY-Materials paradigm, which has emerged over the past decade as a robust and accessible form of self-produced materials prototyping (Ayala-Garcia & Rognoli, 2017; Ayala-Garcia *et al*., 2017; Rognoli *et al*., 2015; Rognoli & Ayala-Garcia, 2021). Initially an experimental trend, it has since become a consolidated practice continuing to evolve through designers' curiosity-driven exploration. It provides tools and techniques for low-cost, informal, and decentralized experimentation independent of industrial infrastructure. At its core lies tinkering: hands-on, intuitive, and iterative making (Parisi *et al*., 2017; Rognoli & Parisi, 2021), intended as a helpful method of material research and development. Tinkering fosters a dynamic interplay between ideation and matter, blending observation and action, theory and practice in environments that provide rapid, rich feedback (Gaver *et al*., 2009; Kelley & Kelley, 2013). Rather than prioritizing control or precision, this approach values openness, failure, and emergence as generative conditions for knowledge production and material innovation.

In this context, material prototyping becomes a mode of thinking through the hands (Nimkulrat, 2012), a situated, reflective dialogue with matter. It is a technical exercise and an epistemological process that generates knowledge through direct experience, situated experimentation, and self-production. This approach is exemplified by the increasing recognition of materials designers, professionals who work at the intersection of design, materials engineering and science, craft, life sciences, the humanities and speculative thinking (Duarte Poblete, Anselmi, *et al*., 2024; Duarte Poblete, Guarino, *et al*., 2024). Their role involves more than simply selecting materials; they must also actively shape and co-develop them through iterative, hands-on engagement. Mastering this practice necessitates an understanding of materials experiences, the capacity to create prototypes that transcend form, and an awareness of the socio-cultural and ecological implications of material choices.

Building on this foundation, the ongoing exploration of alternative, less impactful, regenerative materials has led designers to consider living organisms in recent years. This ecological and speculative mindset has expanded the boundaries of material experimentation, resulting in pioneering approaches where life becomes the medium and partner in the design process. This evolution aligns with and extends the principles of Material Driven Design (Karana, Barati, *et al*., 2015).

Designing with living organisms and microorganisms has recently become a widespread practice within the international design landscape. The intersection of biology, technology, and creative disciplines has led to the evolution of biodesign (Myers, 2012), a field that considers living systems as active participants in the design process rather than passive materials (Camere & Karana, 2018). From this perspective, design is a collaborative process that involves humans and all other living beings. In this model, growth, transformation, symbiosis, and interdependence take precedence over predictability and control. These experimental practices open new possibilities for addressing ecological concerns by challenging extractive models and proposing regenerative alternatives based on collaboration with nature (Antonelli, 2019). From microbial materials to biofabricated structures, biodesign expands materials designers' matter palettes while reconfiguring their role, tools, and methods. This shift reflects a broader cultural and epistemological movement towards ecological thinking and relational ontologies, where materials are not considered inert substances but rather dynamic participants in the creation of regenerative ecologies (Karana *et al*., 2023; Pollini, 2024; Pollini & Rognoli, 2024).

It becomes evident that prototyping is undergoing a profound transformation. While it was traditionally used to test and refine artefacts or materials, in the context of biodesign, it must engage with living entities, such as bacteria, fungi, algae, and other microorganisms that grow, evolve, and respond to environmental stimuli by expressing forms of agency and intelligence. These biological systems resist the logic of rapidity, control, and linear optimization that characterize many conventional prototyping approaches. In this setting, prototypes can be understood as probabilistic artefacts embedded in dynamic, uncertain, and iterative processes rather than stabilizing steps towards predetermined outcomes (Giaccardi *et al.*, 2024). This perspective reinforces our understanding of biological prototypes as living, relational, and agency-driven systems; rather than merely validating form or function, such prototypes act as situated spaces of co-emergence – unstable artefacts participating in the creation of other artefacts and enabling situated, multispecies, and epistemologically generative design practices. Consequently, the laboratory evolves from a production space into a place of care, observation, and negotiation, where designers facilitate conditions for emergence instead of determining outcomes. Within this framework, prototyping is redefined as a relational and situated practice, shaped as much by biological rhythms and ecological constraints as by creative intent.

Experiments conducted in biolab environments suggest that, in the context of biodesign, prototyping is not just a technical act but also an epistemological process. It generates alternative forms of knowledge grounded in observation, co-evolution, and a careful understanding of biological rhythms, dynamics, and uncertainty.

Within this scenario, the notion of "biotinkering" emerges (Pollini, 2024; Pollini & Rognoli, 2024): a practice that combines creative experimentation with scientific knowledge and ethical awareness. Biotinkering is not just about "making with hands"; it responds to the logic of life. Instead of shaping inert matter, biodesigners engage with microorganisms with specific needs, behaviours, and forms of intelligence (Ginsberg *et al.*, 2014; Myers, 2012). This requires a shift in design attitude – from control to engagement and from extraction to collaboration – and necessitates the designer observing, adapting to, and co-evolving with living systems throughout the slow prototyping process.

By tracing the transition from conventional DIY approaches to biodesign, this chapter proposes an expanded and critical vision of slow prototyping, a practice that redefines prototyping not merely as a means to an end but as an open-ended, dialogic, and living process. Through theoretical framing and analysis of three situated case studies, it argues for a broader definition of prototyping in design, transforming the practice into a space of listening, care, and interspecies co-creation (Claire, 2019). This evolving landscape calls for a fundamental shift in the designer's perspective: from control and predictability to adaptability, respect, and co-evolution with living systems. Unlike conventional approaches, often driven by speed, efficiency, and rapid iteration, designing with biofabricated materials requires attunement to the slower, unpredictable rhythms of biological organisms. In this view, prototyping becomes less about optimizing performance and more about cultivating relationships with materials, organisms, and the broader ecological systems in which design operates (Camere & Karana, 2018).

6.2 From DIY materials to biodesign: a shift in the perspective on prototyping

Over the past decade, DIY-materials approaches have emerged as a widely adopted strategy within materials design. Rooted in hands-on experimentation, these practices empower designers to engage directly with matter, bypassing industrial constraints and fostering accessible innovation. Through iterative mixing, heating, testing, and modifying processes, designers explore the potential of raw or waste-based materials, often guided more by intuition than scientific rigour. In this sense, DIY experimentation activates forms of tacit, embodied, and situated knowledge in which material understanding arises through physical interaction and iterative making.

These practices are often characterized by immediacy: the ability to test, fail, and adjust prototypes in short cycles. Whether developing mycelium-based composites, gelatine bioplastics, or starch-based foams, designers working in DIY modalities benefit from short feedback loops that foster creativity and responsiveness. Prototyping here is embedded in a design culture that values speed, visual clarity, and control over form and function.

However, the emergence of biodesign, which engages directly with living organisms, biological processes, and cellular systems, introduces a radical shift in both methodology and mindset. Prototyping in biodesign is no longer about fast iteration or material control but about co-evolving with biological rhythms, where the agency is shared with microbes, fungi, bacteria, or tissue cultures (Myers, 2015). These systems grow slowly, respond non-linearly, and behave unpredictably. The designer must accept delays, failures, and ambiguities as integral to the process.

This shift extends beyond materiality; it demands an epistemological transformation. Those most familiar with living organisms – life science scholars such as biologists – all rely on a common epistemological tool: the scientific method. This method is the primary means for investigating the processes and structures characterizing living systems. To date, the scientific method arguably remains the most effective framework for understanding the complexity of biological phenomena.

Rather than seeking control, the designer becomes a facilitator of conditions, enabling growth, reacting to change, and learning from the living material itself. This shift marks the transition from object-centred design to processual and relational design, where material expression is neither fully predictable nor entirely authored (Ginsberg *et al.*, 2014; Myers, 2012).

6.3 Prototyping with the living: agency, ethics, and co-evolution

Prototyping with living organisms opens up a radically different understanding of material agency. In this context, matter is not inert but active, capable of growth, transformation, and response. Living materials such as bacteria, fungi, algae, or yeast exhibit behaviours that are not entirely predictable or controllable, introducing degrees of autonomy into the design process. As Rognoli *et al.* (2022) note in their discussion of living artefacts, these bio-based systems blur the line between product and process, object and organism. The implications of this shift are profound: the designer no longer interacts with a passive medium but enters into a dynamic and evolving relationship with the living material. Living organisms are open systems that exchange energy and matter with their environment, constantly responding to external stimuli. As such, the design process cannot be based on a one-sided intervention by the designer. Instead, the organism itself contributes independently, reacting and adapting in ways that are often unpredictable. These responses vary depending on environmental conditions, making the designer's role one of observation, interpretation, and dialogue. Understanding these biological mechanisms becomes essential for meaningful interaction, as the act of prototyping becomes a co-creation, designing not *for* the organism but *with* it. Rooted in the principles of slow design, slow prototyping values time, reflection, and ecological responsiveness (Spoelstra, 2023). It embraces delays, irregularities, and uncertainty as essential components of the process rather than obstacles to overcome. What may initially appear as limitations become opportunities for deeper engagement, unexpected discoveries, and more responsible design outcomes. Prototyping becomes a dialogic process shaped by environmental variables such as temperature, light, humidity, and nutrient availability. The artefact itself responds to these factors, and the designer's role shifts from controlling outcomes to enabling conditions for growth. This calls for a new ethical stance rooted in care and attentiveness. Designers must learn to work with, rather than against, the rhythms and needs of biological systems. This ethic of care echoes posthumanist design approaches (e.g., Haraway, 2008; DiSalvo, 2009), which advocate for multispecies respect, interdependence, and co-evolution. Instead of viewing the organism as a tool or resource, the designer becomes a facilitator or caretaker who cultivates relationships across biological and technological domains. In this scenario, the environment plays a crucial role, not as a static backdrop but as a co-author of the prototype.

For instance, subtle shifts in humidity or temperature can dramatically affect the behaviour of bacterial colonies or fungal networks. Designers can work within these fluctuations or choose to actively manipulate them, using bioreactors or controlled ecosystems to "hack" specific outcomes. However, such interventions should come after a period of observation and attunement, where the designer learns what the organism needs before attempting to steer its development. This is the essence of biotinkering: iterative, respectful adaptation based on lived interaction with the organism. The prototype thus becomes an unstable, open-ended system, defined not by completion but by becoming. Its indeterminacy is not a flaw but a feature: a productive space for speculation, emergence, and learning.

This approach repositions the prototype as a living artefact, sensitive to change, deeply relational, and responsive to both human and non-human actors. By embracing this instability, designers are invited into a humbler and situated practice that foregrounds observation, collaboration, and long-term engagement with life itself.

6.4 Biotinkering as design practice

Tinkering is commonly understood as an intuitive, hands-on, and iterative approach to experimentation. It relies on trial and error, exploration, and direct engagement with materials. This approach values openness, unpredictability, and emergence over precision and control. It has proven particularly effective in the context of DIY materials design, where accessible, generative, low-tech, decentralized experimentation can be carried out (Parisi *et al.*, 2017; Rognoli & Parisi, 2021). Thus, tinkering can be defined as a material practice grounded in empirical exploration, improvisation, and an openness to the unexpected – a way of learning and creating through doing, where design outcomes emerge from the process rather than being predefined.

Biotinkering builds upon these principles while introducing specific considerations required when working with living organisms. It can be defined as a design approach that merges creative experimentation with ecological sensitivity and scientific awareness. The presence of living organisms, such as bacteria, fungi, algae or yeasts, transforms the practice: rather than simply manipulating inert matter, designers must engage in a dialogic process with entities that grow, evolve, and respond to their environments. As some scholars (Guarino *et al.*, 2024; Pollini, 2022) highlight, biotinkering is about crafting alongside life, fostering new relations of care, responsibility, and mutual transformation, not just crafting with life.

Unlike traditional tinkering, which is usually driven by intuition and open-ended improvisation, biotinkering requires specific consideration of biological rhythms, the ethics of intervention and environmental complexity. It is based on observation, iterative adaptation, and the co-evolution of the designer, the organism, and the surrounding ecosystem. The designer's role has shifted from that of an author to that of a facilitator of conditions. They must balance creativity with scientific rigour, navigating protocols and operating technical equipment while remaining open to emergence and unpredictability.

This dual capacity often necessitates navigating multiple layers of scale – biological, material, ecological, and technological – thereby introducing significant methodological complexity. To address this, our research adopted a transcalar methodology, which is a conceptual and practical approach connecting actions and insights across different scales – from the microscopic (e.g., microbial behaviour) to the systemic (e.g. environmental impact) (Goidea *et al.*, 2022; Scholte, 2019). Within this framework, biotinkering is one of the operative modes of a transcalar design process offering hands-on, situated experimentation that generates new materials and fosters new ways of knowing and relating to the living world.

This connection was made explicit in the collaboration between the Politecnico di Milano (Materials Design for Transition research group) and the University of Florence (Celli & Cianfano *et al.*, 2025), in which designers and biologists co-developed biofabricated materials by oscillating between laboratory-scale material manipulation and design-scale application scenarios. In this context, biotinkering acted as a bridge between empirical processes and systemic thinking, enabling local material actions to inform broader ecological reflection.

The methodological value of biotinkering lies in its nature as a form of research-through-design (Giaccardi *et al.*, 2024; Pollini, 2024; Vu *et al.*, 2024). Knowledge does not precede action but instead emerges from it. Insights are generated through material interaction: observing how organisms respond to environmental variables, adjusting protocols in real-time, and reflecting on outcomes. As Gatto and McCardle (2016) point out, this integration of scientific and design logic requires the development of a shared language and conceptual framework, one capable of translating across disciplinary boundaries. The designer in this setting becomes a mediator between worlds. They must gain literacy in scientific processes while embracing the ambiguity and open-endedness of design. Biologists, conversely, are encouraged to iterate beyond fixed protocols and engage in framing problems rather than merely solving them (Hall *et al.*, 2019). This mutual transformation is critical to building a genuinely shared epistemological space (Hashemi Farzaneh, 2020). Ultimately, biotinkering is not just a technique but an attitude that values life, embraces complexity, and seeks to co-produce knowledge in ecologically responsive ways. It repositions design as a relational and multispecies practice, where uncertainty, failure, and transformation are not limitations but essential conditions for learning. In this light, biotinkering offers a methodological model for future design education and transdisciplinary research that prepares designers to operate with humility, rigour, and care in collaboration with living systems and scientific partners.

6.5 Slow prototyping: case studies

This section presents three case studies that demonstrate diverse and innovative approaches to biodesign, based on collaborations between designers, living organisms, and material processes. These cases were selected for their use of different biological agents – microbial cellulose, fungal mycelium, and ureolytic bacteria – and explore distinct material behaviours, growth dynamics, and design challenges. Each project demonstrates how biotinkering is manifested in practice by engaging with the agency of living matter, fostering iterative and hands-on experimentation, and reframing the designer's role as a co-creator and facilitator of growth conditions rather than an individual author. Beyond their material outcomes, the case studies also represent different scales of intervention – from craft-scale prototyping to architectural experimentation and bio-cementation – thereby illustrating the transcalar potential of biodesign. Importantly, all three cases exemplify "slow prototyping" as a temporal and methodological attitude: a process of making that is attuned to biological rhythms, open to contingency, and grounded in care and responsiveness. Together, they demonstrate that working with living systems can generate alternative materials and new design values based on sustainability, care, and speculative thinking.

6.5.1 SCOBY leather: experimental material cycles by designer-makers

Symbiotic culture of bacteria and yeast (SCOBY) is a cellulose matrix generated by the fermentation of sweetened tea into kombucha, mediated by microorganisms. This case explores how independent designers and grassroots labs are cultivating SCOBY to prototype alternative “leather-like” materials for fashion and product design.

The process begins with the fermentation of black or green tea using a live culture in wide, shallow containers. Over a period of 10–20 days, a thick cellulose mat forms on the surface. This layer is harvested, rinsed, and dried under controlled conditions to create a translucent, flexible sheet. Depending on drying methods and additives, such as glycerol for plasticization or natural dyes for pigmentation, the material can emulate the properties of leather, parchment, or rubber. What distinguishes SCOBY from synthetic biomaterials is its regenerative nature: it grows from simple, low-cost ingredients and can be cultivated repeatedly with minimal waste. However, its unpredictability, varying thickness, fragility, and sensitivity to humidity require designers to adapt to their expectations and aesthetics. In this context, prototyping becomes less about stabilization and more about attunement. Designers track microbial growth, experiment with fermentation durations, and engage in trial, failure, and transformation cycles. The SCOBY becomes not just a material but a collaborator with its own growth rhythms and constraints.

This practice embodies biotinkering: the iterative and relational making-with-life that values slowness, care, and responsiveness. Rather than seeking industrial scalability, many SCOBY practitioners frame their work as critique, offering alternative narratives about luxury, temporality, and sustainability in material design. As documented by the Future Materials Bank (2023), SCOBY leather exemplifies how microbial processes can be reimagined for production and for rethinking material culture.

6.5.2 Cultivating change: mycelium-based structures by ALEA Studio

This case study investigates the design methodology of ALEA, an experimental studio based in Paris and founded in 2021 by designers Miriam Josi and Stella Lee Prowse. Known for their work on *Back to Dirt*, ALEA cultivates fungal mycelium in combination with agricultural waste to prototype biodegradable materials rooted in regenerative design principles. Their practice is rooted in principles of regenerative design, aiming to develop biodegradable architectural components by cultivating mycelium in combination with agricultural waste.

The research began by identifying locally available waste substrates, such as corn husks, coffee grounds, and sawdust, suitable for fungal colonization. These substrates were sterilized and inoculated with Pleurotus ostreatus, a fast-growing edible fungus. The inoculated matter was then cast into modular moulds of varying geometries to explore the spatial potential of the material. Rather than treating the fungal composite as a static medium, the studio embraced its agency and time-based behaviour. During the growth phase (7–12 days), designers monitored humidity, temperature, and contamination risks, observing how different mould shapes and substrate compositions influenced the density and mechanical properties of the mycelial structures. The resulting blocks were dried to terminate fungal growth and enhance stability. The team emphasized that the final form was not entirely "authored" but emerged from a co-productive process between the designer, organism, and environment. This approach exemplifies slow prototyping: iterative, relational, and deeply embedded in biological temporality.

ALEA's practice highlights how prototyping in biodesign shifts from form-driven processes to condition-making, creating environments in which living matter can express its own logic of formation. It also reveals how biodesign can serve speculative and pedagogical functions, challenging extractive paradigms in architecture and material culture.

6.5.3 Biocalcification with Sporosarcina pasteurii

This case study explores the potential of *Sporosarcina pasteurii*, a ureolytic bacterium capable of inducing microbially induced calcite precipitation (MICP), in the development of biofabricated composite materials made from recycled aggregates and textile fibres. The aim was to investigate biocalcification as a sustainable alternative to cement-based binding, proposing a regenerative approach to material assembly.

The project emerged from a collaboration between designers and biologists, initiating a cross-disciplinary dialogue to understand the conditions required for bacterial growth and calcification. The early stages of experimentation were informed by microbiological protocols and consultations with laboratory experts, who provided insights into the handling and environmental requirements of S. pasteurii. The substrate was prepared using sieved recycled concrete aggregates combined with discarded textile fibres, specifically linen and cotton selvedges, chosen for their porosity and structural entanglement. This porous matrix was designed to host bacterial activity and facilitate the diffusion and crystallization of calcium carbonate throughout the composite.

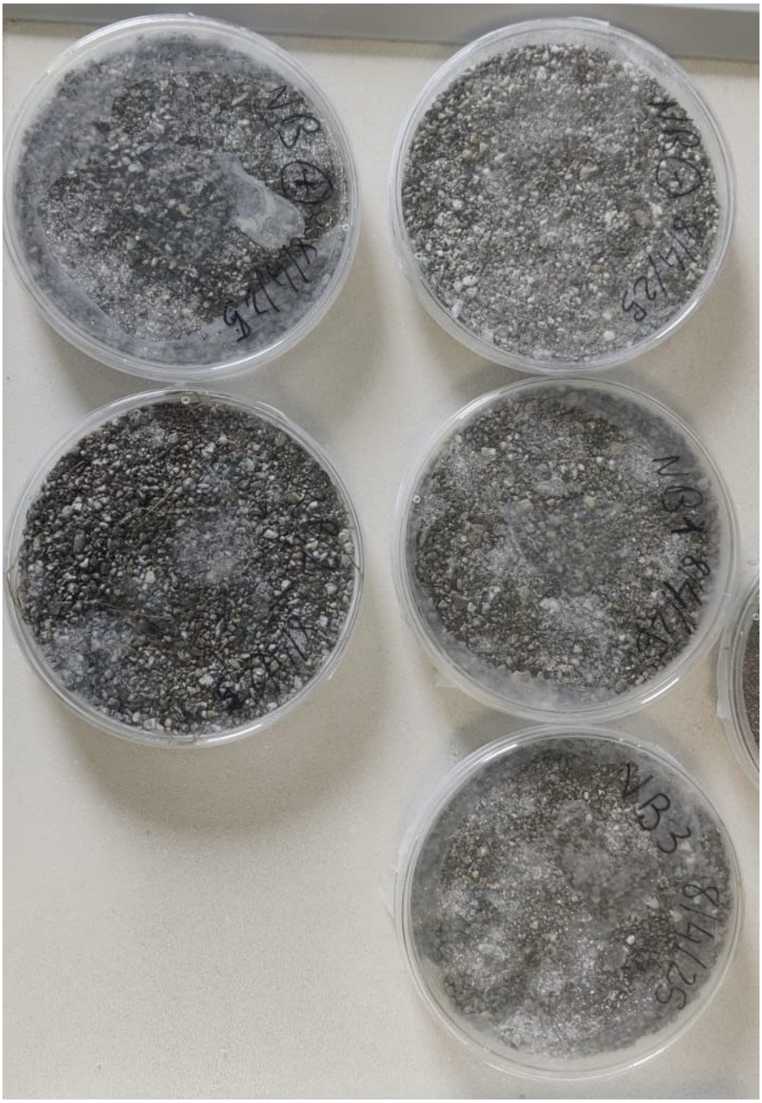

Figure 6.1.
Petri dishes with the bacterium (S. pasteurii) and the substrate (recycled concrete).

The intended treatment consisted of two main phases: first, the application of the bacterial culture, followed by immersion in a calcifying solution that triggers mineral bonding. This sequence was designed to initiate a bio-cementation process, transforming loose particles into cohesive and structured material through the organism's metabolic activity. This experiment (Figure 6.1) positions material making as a co-productive process, where design parameters, such as fibre orientation, aggregate size, and form, are carefully tuned in response to the biological rhythms of the living agent. The designer's role shifts from author to environmental facilitator, orchestrating conditions for life to act as a materializing force.

Biocalcification is not only a method of consolidation but also a design gesture: a practice where industrial waste and microbial life come together to form hybrid matter with dual origins, technical and biological. The result is a speculative material language that redefines notions of authorship, temporality, and sustainability in design (Cianfano, 2025).

6.6 Discussion

The three case studies presented – SCOBY-based microbial cellulose, ALEA's mycelium biofabrication, and the bio-calcification process using Sporosarcina pasteurii – provide different yet complementary insights into slow prototyping in biodesign. Despite their differences in biological agents and application contexts, the studies converge around a shared methodological approach that is grounded in iterative experimentation, attention to biological temporality, and relational engagement with living materials.

In each case, slow prototyping is a conscious departure from conventional design workflows, which prioritize control, predictability, and efficiency. Instead, it embraces unpredictability, emergence and continuous adaptation. Designers shift from acting as individual authors to becoming facilitators who create and maintain conditions for life to flourish and influence material outcomes. This requires close observation of biological rhythms, responsive adjustments through feedback loops, and acceptance of failure and transformation as integral to the process.

The case studies also operate across different scales of intervention, from small-scale DIY SCOBY fermentations to architectural mycelium composites and experimental bacterial mineralization, demonstrating how biotinkering fosters deeper attunement to time, material instability, and ethical responsibility as a mode of making-with-life. Rather than viewing slowness and uncertainty as limitations, these practices reveal them to be generative conditions that encourage innovation through care, co-evolution, and critical reflection.

Ultimately, these examples demonstrate how slow prototyping challenges established ideas about material production and authorship. They open up the possibility of new material cultures that are rooted in ecological sensitivity and transdisciplinary collaboration. At the same time, they redefine the role of the designer as one of co-creation with biological entities. This shift produces innovative and sustainable materials and invites broader reflection on temporality, responsibility, and the ethics of intervention in design practice.

6.7 Conclusions and future developments

With the emergence of biodesign, prototyping is undergoing a profound epistemological and methodological transformation. No longer conceived merely as a phase in product development, it becomes a relational and situated practice – one in which knowledge is co-produced through direct engagement with living systems. The inherently interdisciplinary nature of biodesign – where design converges with biology, engineering, environmental science, and the humanities – demands a reconfiguration of roles, methods, and expectations.

As demonstrated throughout this chapter, prototyping with biofabricated materials involves navigating a dynamic negotiation between the intentions of the designer and the emergent behaviours of biological agents. Far from being passive recipients of form, organisms such as bacteria, fungi, or algae express agency, grow according to their own temporalities, and resist the logics of speed, control, and predictability that often characterize conventional design paradigms.

In this context, the designer is called to adopt a new stance – one rooted in attentiveness, humility, and care. Designing becomes a dialogic process, not of imposing form, but of listening and negotiating with other-than-human collaborators. Prototypes are not static endpoints but evolving systems: spaces of becoming shaped by feedback, uncertainty, and ecological interdependence.

This shift has significant temporal implications. Biological growth unfolds on a slower timeline than industrial processes. What might be perceived as limitations – delayed outcomes, irregular behaviours, or lack of control – are, within the framework of slow prototyping, reframed as opportunities. Time becomes a resource for reflection, observation, and co-evolution. Failure becomes a site of learning. Instability becomes a condition for emergence. As Spoelstra (2023) suggests, these are not flaws to eliminate, but characteristics to cultivate within a new design logic.

The case studies discussed in this chapter – from microbial cellulose and mycelium structures to bacterial mineralization – have illustrated how biotinkering enables this shift. They exemplify slow prototyping as a generative method, capable of producing not only innovative materials but also new design values based on sustainability, multispecies care, and systemic awareness.

Looking ahead, this approach invites further exploration along several lines. First, there is a need for new educational frameworks that prepare designers to operate in hybrid labs, bridging intuitive practice and scientific method. Second, future research should continue to develop transcalar methodologies capable of connecting microscale material processes to macroscale ecological and cultural questions. Finally, as the field matures, it will be essential to engage in critical reflection on ethics, responsibility, and the politics of life at the core of biodesign.

Rather than offering fixed models or prescriptive methods, this chapter contributes to an ongoing, evolving conversation. In embracing the uncertainties of working with living matter, slow prototyping opens up space for experimental, inclusive, and ecologically responsive forms of design – ones that are not only about making things, but about making sense, together with the living world.

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PART 3

Comprehending through prototypes

7. Turning abstract data concrete: drawing and tinkering with data

Ayşe Özge Ağça, Jacob Buur

7.1 Introduction

Data visualizations and data physicalizations have become popular methods of making abstract data tangible in design (Haliburton *et al*., 2023; Mortier *et al*., 2014). Recently, the interaction design community has introduced promising approaches to involve a broader range of perspectives in digital data engagement (Huron *et al*., 2017; Jansen *et al*., 2015; Sauvé *et al*., 2024). Lupi and Posavec's (2016) *Dear Data* presented highly unconventional yet human visualizations of self-tracking data. Two graphic designers communicated hand-drawn notations via postcards between London and New York. They counted, for instance, the number of doors they passed in a week, the number of complaints they heard, and how often they laughed – all in compelling visual diagrams.

Within business anthropology, Anderson *et al*. (2009) have shown how people's digital data may be visualized in a way that enables them to reflect on their practices and explain what the data means. 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 the effect of interactive data products (Laschke *et al*., 2011). Data physicalization was proposed to shift data visualization 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). Using "object theatre", Karyda *et al.* (2020) have pushed even further in devising data objects that prototype digital self-tracking data.

Developed from our EKSIG 2023 paper (Ağça & Buur, 2023), this chapter describes an experimental investigation to develop data drawing and data tinkering methods (Figure 7.1) that support individuals in experiencing their own consumption data. We hope to challenge our participants to reflect on their practices and ultimately provide incentives for more sustainable habits. We encouraged 40 graduate design students to *draw* their water consumption and waste recycling. After comparing and discussing their notations, we challenged the cohort to *tinker* with data using tangible materials. In the following, we analyse the results to better understand what it means to draw and to tinker with data, as well as the experiential knowledge it elicits. By drawing on Gestalt principles and the theory of affordances in the analysis, we boldly suggest that such terms as "data-gestalt" and "data-affordance" may help us prototype engaging data.

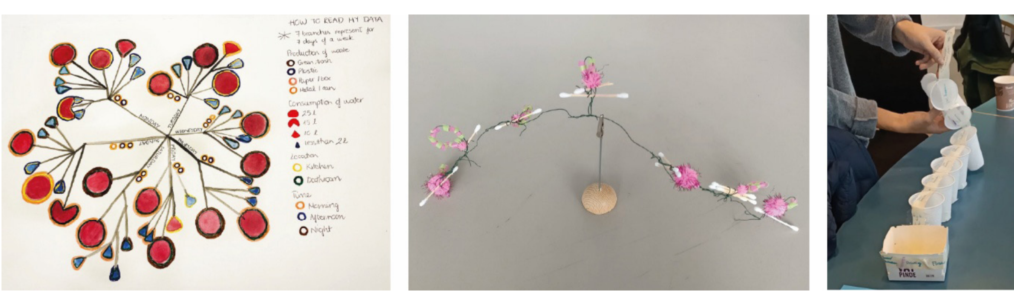

Figure 7.1.
Examples of a data drawing (left), a data tinkering (middle) of weekly water consumption, and how one participant engages with tangible data (right).

7.2 Methods we used

To investigate how young people engage with data about their consumption, we challenged the 40 design students across two studios to record their individual use of water and recycling of waste for one week. The aim was to understand their opinions on behaviour change for further studies. The United Nations (UN) Global Sustainable Development Report 2019 argues that young people are key agents of sustainable behavioural change (Independent Group of Scientists appointed by the Secretary-General, 2019). As we can see from the Fridays for Future movement (https://fridaysforfuture.org) and the UN Sustainable Development Goal (SDG) *Bringing Data to Life* (Department of Economics and Social Affairs, 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 inspired by the *Dear Data* project (Lupi & Posavec, 2016). The two studios produced a total of 32 data drawings, which we co-analysed with the participants on the whiteboard using dimensional analysis (Kools *et al*., 1996) and affinity diagramming (Kawakita, 1982).

As dimensions, we provocatively asked, for instance, "Who uses the most water? Which drawing has the 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 decipher, others were easier as they built on well-known visual cues. We video-recorded the analysis sessions to understand how participants talked about their consumption data and how they related to their data drawings (Figure 7.2, left).

Following the co-analysis, we became curious about how to conceptualize the clusters. With inspiration from Gestalt principles (Ellis, 1999; Koffka, 1963), we realized that one may recognize data patterns not just conventionally in tables and graphs but also tallies, circles, units, symbols, and concepts.

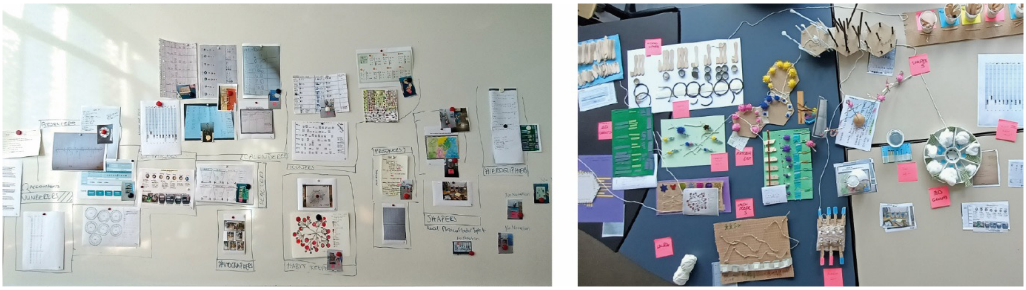

Figure 7.2. The co-analysis of data drawings (left) and data tinkerings (right).

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 gave the participants a standard set of consumption data from one family (Table 7.1) and challenged them to build physical objects expressing the data in a one-hour session. The two studios produced a total of 30 data tinkerings. After each explained their data tinkering, we engaged the participants in co-analysis and recorded how they talked about their prototypes, Figure 7.2 (right).

Activity in litres	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

Table 7.1. The data set of one family's water consumption for a week was used for data tinkering.

Following up on the co-analysis, we realized that the theory of affordances (Gibson, 1979; Norman, 2013) can help identify data-affordances: What did participants expect one might do with their data physicalizations? What acts might they afford? We grouped the constructs according to what the materials and shapes signify and what they invite us to do, as expressed by the design students in their narratives and bodily actions during the presentation.

In the two subsequent years, we ran similar teaching processes to verify the results and see if we could encourage design students to make data intelligible by introducing the concepts of data-gestalt and data-affordances upfront.

In the following section, we will recap the theories of Gestalt and affordances and illustrate examples 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 their habits. In a final section, we will discuss how data-gestalt and data-affordance can inspire design.

7.3 Drawing data-gestalt

Information visualization is a core technique for visual representation of abstract data to aid cognition for participants of different disciplines (Ellis, 1938/1999; Evergreen & Metzner, 2013). Ware (2012) suggests that data visualization supports external cognition and humans' visual ability to identify patterns, as expressed in the typical saying: "I see what you mean!".

While the word *gestalt* simply means *pattern*, Koffka's Gestalt principles discuss quantity, order, and meaning, helping us understand the relationship between the meaning of data and seeing the data (Koffka, 1963; Norman, 2013). Wertheimer suggests "prägnanz" [group making] as a main principle that predicts the interpretation of sensation (Ellis, 1938/1999, pp. 54–55). He explains that it easily translates into a set of basic design principles such as proximity, similarity, connectedness, continuity, relative size, and common fate (Ellis, 1938/1999, p. 64). While valid on their own, they are most often used in intricate combinations to create a semantic whole.

Gestalt theory is expressed in *laws*: The law of proximity states that things that are close together are perceptually grouped, forming patterns. Individual patterns can also determine how they are grouped in the law of similarity. The law of connectedness explains how graphical grouping is substantiated by lines, 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 in terms of principles, we begin to form specific patterns. These patterns trigger our cognitive visualization 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), the three main motivations for creating visualizations are to discover, present, and enjoy. In the *Dear Data* project, we can see all three motivations at play in the hand drawings, which aim to increase engagement with mundane, daily data (Lupi & 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.

The participants' drawings show data-gestalt. We identify seven data-gestalt patterns, which we express in nouns in Figure 7.3. 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 such as counting, tabulating, and coding, as noted in the handwritten notes. The group we named *concepts* combines drawings that are more abstract or complex. Initially, it was not easy to relate these drawings to one another based on Gestalt principles, and we had only 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 preempts a point we will make later when analysing the data tinkerings in the second stage.

7.4 Tinkering data-affordance

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 agency have the capacity to do something or act like something. He explains the boundaries between daily things and ourselves through practical arrangements, which are embodied in the activities of our bodies.

Gibson (1979) introduces *the concept of affordances* to refer to the properties or opportunities that people perceive in their environment. They provide *act-able* features that encourage people to take action. 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" (p. 19). He claims that affordances are not always perceivable; they can be open to interpretation and look ambiguous. As he wants to include designed cues (such as icons), Norman (2013) suggests the term *signifiers* (p. 19). 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 inviting the user to the right action" (p. 285). They criticize 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, [...]" (p. 288).

To design tangible interactions with the abstract concept of data, several methods for physicalizing data exist. Jansen *et al.* (2015) view data physicalization as a visualization technique that enriches data communication and the impact on data presentation. 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.

Tinkered prototypes have data-affordances. 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 similar to the data-gestalt analysis. Our analysis shows how data-affordances may be formulated as count-able, rotate-able, hang-able, etc. (Figure 7.4).

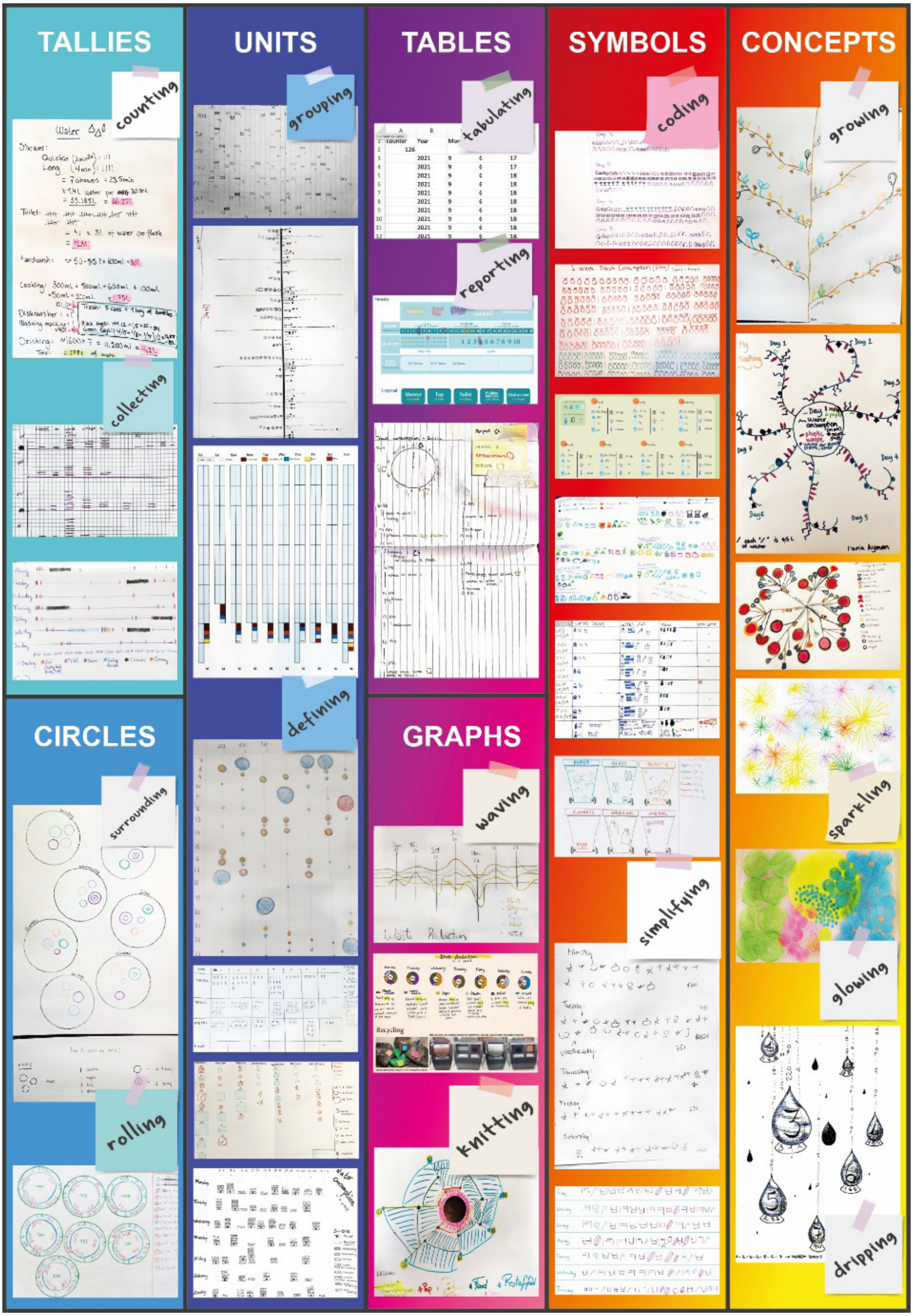

Figure 7.3.
Seven data-gestalt patterns resulting from the analysis of 32 hand-drawn data visualizations.

Figure 7.4.
Ten data-affordances based on the clustering of 30 data tinkering prototypes.

7.5 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 design students talk about when presenting and comparing their visualizations. 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 design student is surprised to compare her shower figures with others':

P4: "I used 300 litres per shower. The shower runs for 20 minutes, and I have never stopped the water before. This week, I just kept it that way, so the data is real. From now on, I mean today is Monday, and I will stop the water when I shampoo myself. That is less water, I guess."

These are the first indications that data drawing raises awareness of how much you consume and may even lead to behavioural 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."

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

When it comes to building consumption representations 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 means. The concept of *how much* is central to how the participants select materials. When showing a long piece of plastic in his prototype, for instance, one design student says:

P7: "You can't really understand how much you used water [sic] 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 litres…"

One student finds a creative solution: In her prototype, each weekday is represented by a cup with beans in numbers corresponding to the data. As the cups are connected, she can flex the construct to collect all the daily consumption into one cup (Figure 7.1, right):

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

Metaphors play an important role when the participants express 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…"

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 participants express sustainable values in their prototyping:

P14: "When you flush, you will crush… flowers mean you are very clean in [sic] these days…and I put this pig here because you use 35 litres here."

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

7.6 How the terms relate

We have analysed how the data drawings of particular data-gestalt may have inspired data tinkering with particular data-affordances. 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 participant brings inspiration from their data drawing across to the data tinkering. In other cases, the design students take inspiration from one another's works. In the following, we have selected the five most clear examples from our analysis.

Does *tallies* gestalt inspire *count-able* affordances? One participant, whose data drawing we characterized in the *tallies* group, used cotton buds 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 7.5a). We recognized this as a *count-able* affordance: "I tried to play with the materiality like the cardboards were the days I spent at home. [...] The cotton buds show the overall water consumption for the days."

Brunswick (1952) expands 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 how they affect it. Storkerson (2009) explains Brunswick's term *perceptual constancy* as "the organism [using] multiple cues vicariously to deliver the perception of a constant object in different locations or at different angles". We perceive the cotton buds as similar to the drawn tallies as they both offer the affordance of counting. Gibson (1979) actually based his affordances theory on Gestalt theory, as each thing has a way of indicating what acts it invites.

***Circles* and *rotate-able* constructs.** In the *circles* group, one participant transfers her *circle* concept from the drawing to using different circular objects with some proximities and relativities to represent the data. This means she can now *rotate* the bottle caps and paper plates to provide different views of the data on them in Figure 7.5b. "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 conveys a particular view of data, the rotate-able tinkered objects allow for manipulation, enabling the viewing of data from several angles.

***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 7.5c. The strings make it possible to trace the data with a finger; it is *trace-able.* The days are displayed similarly, with sharp lines in both data drawing and data tinkering. As said by one participant: "This is flushing [traces the blue string], this is showers [yellow string], and you can see how fluctualizing [sic] and drinking [grey string] is always the same."

***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 participants, the colour and material choices by the law of similarity support the links between the *sparkle* data drawing and the *squeez-able* tinkering (Figure 7.5d). One participant says: "This is flush. [He crushes the plastic cup, turned upside down and roughly surrounded by a ring.] The brown-coloured ones show the final amount we use for the toilet. And the weekend looks browner because, you know [Laughs]."

Did *growth* gestalt inspire a *fly-able* affordance? In Figure 7.5e, the participant employs the same shapes and patterns as in her drawing, which we referred to as *growth*. In the tree growth drawing, the branches grow in proportion to the amount of waste; in the *growing* and *flying* tinkering, the balloons grow in proportion to higher data numbers. Both have a centre of gravity and the same direction of growth 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."

As Brunswick's theory (1952) explains, gestalt is not a simple perception of elements, but an intricate negotiation of multiple cues between the object and its 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. However, 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 recognizing attributes but also in inspiring future designs of data prototypes. We have indicated links between data-gestalt and data-affordances using similar colour codes in Figure 7.3 and Figure 7.4.

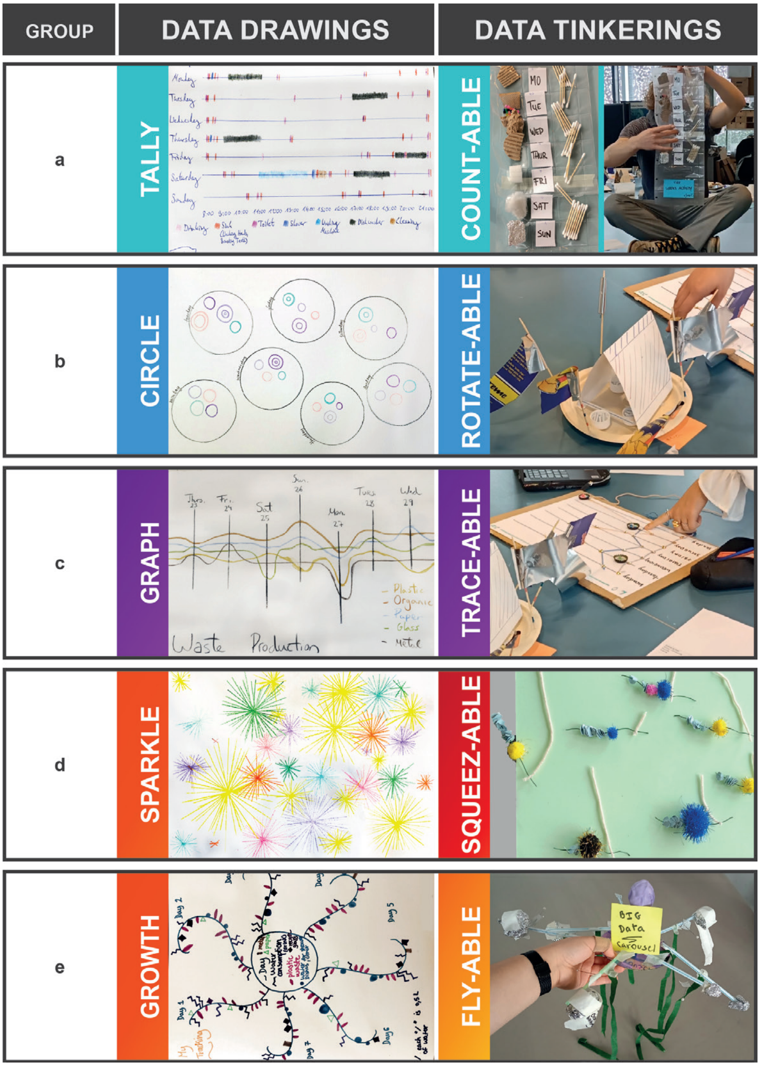

Figure 7.5.
The clustering of data drawing nouns and data tinkering adjectives: a tally and count-able (a), a circle and rotate-able (b), a graph and trace-able (c), a sparkle and squeez-able (d), and a growth and fly-able (e).

7.7 Data-gestalt and data-affordance as design drivers

What is the value of the terms – data-gestalt and data-affordance – that we propose? Our goal is to better understand how abstract data may be given an intelligible form – visual or physical – to make it easier to understand, engage with, and act upon. Our final experiment aimed to investigate whether the theoretical perspectives can support designers tasked with making data intelligible. In a subsequent teaching year, we investigated whether our concepts could help widen the design space when introduced upfront. We used the terms in two ways:

1. Once the students had completed their data drawings, we asked them to co-analyse the drawings using the data-gestalt terms.
2. When they started data tinkering, we printed labels with the data-affordance terms and asked them to pick one or two they wanted to aim for.

The topic this year was "transport", so the students had tracked their own means of transport for a full week leading up to the project start. We provided them with posters and stickers composed of data-gestalt nouns and data-affordance adjectives, enabling them to analyse one another's work and articulate their own data representations. We video-recorded the entire data visualization and physicalization process, including the sensemaking activities and brief presentations. As in previous years, when we had completed the data-gestalt analysis, it was exciting to see if the students would be able to use the data-gestalt terms to characterize the variety in their data drawings.

One student counts the data by the purpose of transportation with colour-coded abacus beads in (Figure 7.6a) and explains why she puts her drawing in the *tallies* group: "I think it is because of *collecting* action from tallies [the action word from the poster under the tallies group we provided the students]". Another student, working within the *circles* gestalt, described her data drawing developed around the concept of a clock (Figure 7.6b), as follows: "I tried to do like a clock, so I separated the cycle into eleven parts, and on some days, I have to [cycle] for half the time, so I tried to make it like 3:30 to 4:30." She explains that the clock-shaped days represent variations in size based on the intensity of transportation activities throughout the day. While she acknowledges that her data drawing might belong to the *concepts* group because of the abstraction of an artefact, she finds it more fitting for the *circles* group due to its circular structure.

When we look at all the instances of students relating their data drawings to the data-gestalt terms, it is indeed the case that the terms *work*. The students appear at ease with the analysis.

During the data tinkering session, the students are challenged to pick one or two data-adjectives in the form of colour-coded labels that refer to the poster (Figure 7.4) as inspiration for their prototypes, and explain the connection in their presentation.

The students explain, for example, "long lines represent long activity days as *catch-able* data," and "objects of different weights represent the varying challenges of transportation as *throw-able* data" (Figure 7.6c). One student bases her design on the *rotate-able* affordance. In the presentation, she gestures circular motions with her fingers (Figure 7.6d) to describe the transportation data as "a dog chasing its tail":

It is a cycle as the way I understand, it is the dog, [she grabs a purple soft ball and squeezes] furry, you know, Monday, Tuesday [sic] and Sunday and then repeats [shows circling with her fingers], and this is the train, tram [grabs ice-cream sticks and plays back and forth], and you can go around.

Students sometimes discover accidental affordances in their prototypes. For instance, with the *hear-able* label, two classmates demonstrated different ways of shaking or stirring ice cream sticks to produce sound. In the discussion, participants suggest further affordance labels, such as *shake-able*, *stick-able*, *burn-able*, and *throw-able* based on their prototyping experiments.

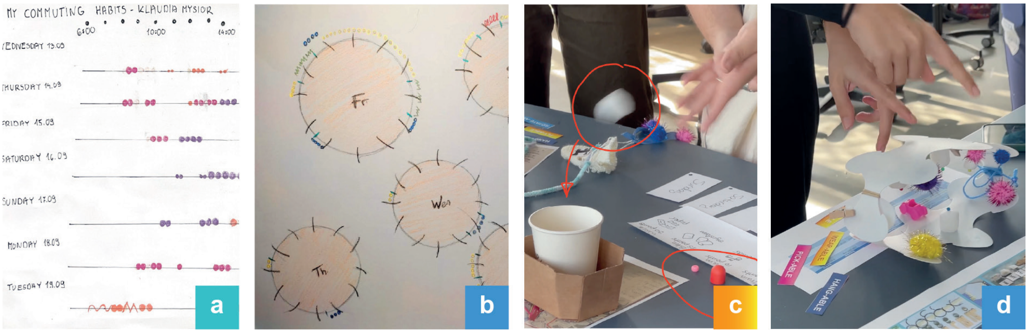

Figure 7.6. Participants use the data-gestalt and data-affordance terms as a driver for their data drawings and data tinkerings.

Based on our observations, we suggest that familiarity with the idea of data-affordance and with the data-affordance terms contributes to richer data physicalizations by introducing greater diversity, dimensionality, and perspective.

How did the provided materials influence the physicalization designs of the data? 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** (e.g., 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.

7.8 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. It triggers the participants to share experiences of consumption and recycling with their peers by comparing and clustering 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 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 tinkering 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 participants, through data drawing and prototyping, become aware of their consumption habits and possibilities for behavioural changes. We observe that the raised awareness of the participants is a consequence of data prototyping, rather than simply 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 exhibit similar colours, shapes, or symbols in both their visual and physical expressions. This becomes even more pronounced when we challenge participants to use the concepts actively as inspiration. The final experiment demonstrates that our terms, data-gestalt and data-affordance, can assist designers in engaging more visually and physically with data, thereby making abstract data easier to grasp, interact with, and act upon.

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8. Hands-on thinking: prototyping as a pathway to theoretical understanding

Sisse Schaldemose

8.1 Introduction

Prototypes are commonly used in design to explore, test, or communicate ideas before they take final form. As Houde and Hill (1997) define it, a prototype is "any representation of a design idea, regardless of medium" – a definition that opens the possibility of using prototyping well beyond product development. This chapter investigates how the act of prototyping may support learning processes, particularly when it engages with complex theoretical content in a discipline other than design in higher education.

Using tangible materials as part of a design process is a well-established approach within design research and participatory design (Brandt & Grunnet, 2000; Mitchell & Buur, 2010; Stappers & Sanders, 2004). In these contexts, such materials are not valued for their realism or fidelity, but for their capacity to spark imagination, facilitate dialogue, and support exploration. As Mitchell and Buur (2010) argue, the effectiveness of these "things to think with" lies in the conversations they provoke and the associations they inspire (p. 30).

In contrast to their widespread use in design, tangible learning objects – often called manipulatives – are rarely employed in adult education, where learners are typically expected to engage with abstract representations and symbolic reasoning (Schneider, 2017). Yet in disciplines like social work, where theories must eventually translate into practice, this assumption may underestimate the pedagogical value of material engagement.

Social work students are frequently presented with theories in the form of diagrams, graphs, figures, and other 2D visual models. While these representations may help reduce complexity, they also risk appearing static and complete. Drawing on Tim Ingold's (2010; 2012) distinction between *objects* and *things*, such visual models can be understood as *objects*. Drawing on Heidegger's essay "The Thing", Ingold (2010) writes: "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" (p. 4).

In this view, prototyping becomes a *form-giving* practice – an open-ended, dynamic process that invites thought, reflection, and transformation. Quoting painter Paul Klee, Ingold (2010) reminds us: "Form is the end, death. Form-giving is movement, action. Form-giving is life" (p. 2).

Inspired by the concept of design anthropological theory instruments (Buur *et al.*, 2022) and drawing on a research-through-design methodology (Zimmerman *et al.*, 2010), this chapter explores how prototyping can help social work students move from passive reception of theory to active interpretation. It investigates how tangible materials may serve as mediators of theoretical understanding – facilitating engagement, prompting dialogue, and creating space for uncertainty and negotiation of meaning.

Rather than offering prototyping as a ready-made solution, the chapter frames it as a pedagogical provocation: an invitation to rethink how theory is introduced, represented, and explored in education. Through a series of workshops involving students and educators, the chapter examines what happens when theory is brought into form – not as truth, but as something to be tested, handled, and thought through together.

8.2 Methodology

This study is grounded in constructivist and social constructivist learning theory, which emphasizes that learning is not the passive reception of information but an active, situated process. Drawing on the work of Jean Piaget, constructivist theory posits that knowledge is formed as learners integrate new experiences into their existing cognitive frameworks (Dolin, 2015). Social constructivist perspectives, following Lev Vygotsky, further highlight the importance of interaction, culture, and artefacts in the formation of understanding (Ulriksen, 2016).

These theoretical foundations align with the study's interest in how the physical act of modelling theory might influence students' comprehension. Accordingly, a qualitative, exploratory approach was chosen, centred on a series of collaborative workshops. The research employed a research-through-design methodology (Zimmerman et.al., 2010), which fosters knowledge generation through iterative making and reflective engagement with materials and participants.

I conducted four workshops with students from the social work programme at VIA University College in Aarhus, each lasting approximately two hours. All participants were recruited from Module 8, a midpoint in the three-and-a-half-year curriculum, which the students reach after completing a six-month internship. By this stage, they have already encountered various theoretical frameworks both in coursework and in practice. Because I was teaching the module at the time, I introduced the research project during class, explaining my interest in materializing theory and openly sharing my uncertainty about where the project might lead. This informal, personal introduction likely contributed to the student's willingness to participate. Fifteen students expressed interest – more than anticipated, given that participation was extracurricular – but due to scheduling constraints, a maximum of eight students attended each workshop.

The first two student workshops focused on encouraging participants to create physical representations of theories they already knew. A variety of craft materials were provided while traditional drawing tools were deliberately excluded. The intention was to prompt three-dimensional thinking and reduce reliance on familiar two-dimensional visualization strategies.

Based on insights from these sessions, I conducted two workshops with colleagues, aimed at developing "theory instruments" (Buur *et al.*, 2022) that could be introduced in the subsequent student workshops. In the third and fourth workshops, students were presented with two preliminary theory instruments developed during the earlier sessions with colleagues. These instruments were based on Bronfenbrenner's (1979) ecological systems theory and Bourdieu's (1986) forms of capital. Rather than being finalized tools, they were left open and provisional. The students were asked to engage with the instruments by interpreting, critiquing, and suggesting improvements – thus positioning them not only as users but also as co-developers. This setup allowed for deeper reflection on both the form and function of theoretical representations and further explored the potential of materialized theory as a site of dialogue.

All workshops were video-recorded, and the recordings were subsequently reviewed in full. The analysis was conducted using the KJ-Method (Scupin, 1997), a qualitative technique that supports the identification of patterns, themes, and categories through iterative clustering of observations. This method was chosen to capture the nuances of students' interactions, bodily engagement, verbal reflections, and moments of insight or confusion as they emerged throughout the prototyping process. Based on the clustering process, five interrelated themes emerged that informed the structure of the analysis: (1) how materials shape and constrain theoretical representations, (2) how physical engagement can support conceptual understanding, (3) how collaboration and dialogue contribute to meaning-making, (4) how familiar visual models can both support and hinder theoretical reflection, and (5) how immersion and sustained focus can foster a flow state that deepens learning. These themes are explored in depth in the following sections, each anchored in examples from the workshops.

The goal of the analysis was not to quantify learning outcomes but to explore how tangible engagement might mediate theoretical understanding and invite new forms of reflection.

8.3 Insights from the workshops

The following sections present key findings from the six workshops conducted with students and educators. These insights are grouped thematically to highlight different aspects of how prototyping influenced the participants' engagement with theory.

8.3.1 Choosing and shaping materials

The materials made available to students during the first two workshops played a crucial role in shaping not only the final models but also the way students engaged with the process of theory construction. Initially, students were offered a selection of basic craft supplies: clay, pipe cleaners, pom-poms, toilet paper rolls, glue, string, and rubber bands. Traditional drawing tools were deliberately excluded to shift attention away from two-dimensional representations and encourage spatial, embodied exploration.

Despite this intention, most of the models produced in the first workshop were essentially flat in form – nearly two-dimensional in appearance – and could arguably have been drawn just as easily. This observation prompted a revision in material selection for the second workshop. New components were added, including shaped building blocks and Styrofoam balls. The change had an immediate impact: every model created in the second session was fully three-dimensional.

These new materials shared an important quality – they resembled familiar forms. The Styrofoam balls could easily be interpreted as heads or bodies, and bridge-shaped blocks naturally evoked the idea of connection or transition. This *symbolic suggestiveness* seemed to lower the threshold for participation and stimulated students' imaginative interpretations. For instance, one student used a bridge-shaped block to represent "bridging social capital" (Putnam, 1995), while another employed a similar element to express the outcome of empowerment.

The choice of materials and the meanings assigned to them also resonate with Donald Schön's (1992) concept of a "reflective conversation with the materials." As he observed in his study of design students, the same set of materials can be perceived and used in radically different ways depending on what the maker brings to the situation. The building blocks, in this case, functioned as *signifiers* in the sense described by Donald Norman (2008): material forms that carry embedded cues, sparking ideas or offering metaphoric connections.

For students unaccustomed to creative or artistic activities, these signifiers were particularly helpful. Rather than facing a blank slate, they could draw on the latent symbolism of the material to support their translation of abstract theory into tangible form. This suggests that materiality is not merely a vehicle for expression but an active participant in shaping how theory is understood, embodied, and externalized.

8.3.2 Thinking through the hands

For many of the participating students, the process of modelling theory using physical materials proved both unfamiliar and cognitively demanding. Several participants described the activity as challenging but also highly engaging. As one student reflected, "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 have to think differently and creatively" (Workshop 1, Participant 1).

Despite being an extracurricular activity, the workshops generated a high level of concentration and focus among participants. Both verbal expressions and non-verbal behaviours indicated deep engagement with the task. Students were not simply reproducing theoretical content; they were *thinking through their hands*, exploring, adjusting, and reinterpreting ideas as they manipulated materials. This aligns with the constructivist understanding of learning as an active and situated process (Ulriksen, 2016).

Although students were working with their hands, they often highlighted the mental effort involved. One student remarked, "To me, it's candy for the brain. Sitting here, being creative, working with my hands – it's focus training. I didn't go into this thinking 'I'm 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). Another noted: "You force yourself to think in a completely different way. You don't think about the time because you're so consumed within theory" (Workshop 2, Participant 5).

This mode of engagement suggests what Schön (1992) refers to as a “reflective conversation with the materials of a design situation” – a reciprocal process in which the material *talks back* to the maker, prompting ongoing interpretation and adaptation. Students were not executing pre-planned models but instead entered into an iterative, tactile dialogue with the materials at hand. The act of choosing, bending, rejecting, and recombining materials appeared to structure and support their cognitive process.

This observation also resonates with the notion of sensorimotor coupling (van Dijk, 2013), which emphasizes the entanglement of bodily movement and cognitive activity. Rather than using the materials as external scaffolds for cognition, as described in extended mind theory (Clark & Chalmers, 1998), the students experienced the process as mentally demanding. Their interactions with the materials were not about simplification, but rather about expanding the space for reflection and sense-making.

As students moved back and forth between material manipulation and theoretical reasoning, the modelling process became a form of embodied inquiry. It required them to grapple with the core structures and assumptions of the theory they were representing, and in doing so, revealed both their understanding and their uncertainties.

8.3.3 Prototyping together

After completing their models, students were invited to present and discuss them with one another. These conversations revealed how physical representations of theory could act as catalysts for deeper reflection and collaborative meaning-making. In many cases, students’ initial models were challenged or expanded through dialogue with peers, prompting them to revisit their assumptions or reconsider theoretical concepts.

A clear example of this dynamic emerged in a discussion around a student’s model of empowerment (Figure 8.1). Another participant pointed to the model and asked: “How do you suppose one gets from there to there? [pointing to the red and the green 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?” (Participant 2, Workshop 1). This question highlighted a missing element in

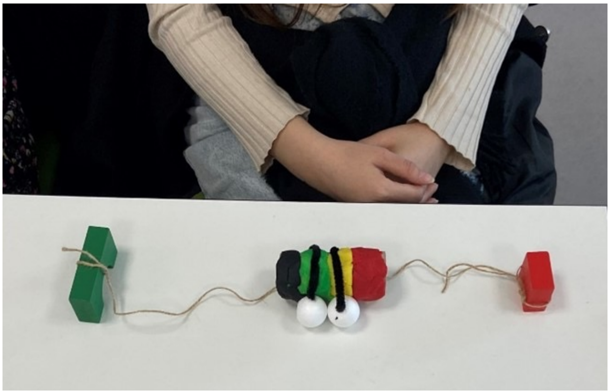

Figure 8.1.
A student's model of empowerment.

the model: the process itself. The student who had built the model responded by acknowledging that she had not considered that aspect: "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" (Participant 3, Workshop 1).

What followed was a collaborative exchange of suggestions – adding a ball that could move through the tunnel, introducing reversible elements, or incorporating unexpected influences. These suggestions did not just improve the model; they deepened the group's collective engagement with the theory itself. As one student concluded: "Well, just look, a completely 'dead' model got brought to life just from us talking about it." (Participant 2, Workshop 1).

This episode exemplifies what van Dijk (2013) refers to as "socially situated practice", in which artefacts become meaningful through social interaction (pp. 42-49). In this case, the prototype served as a shared reference point – a concrete object that anchored the group's thinking and allowed abstract ideas to be explored together. Rather than relying solely on verbal explanation, students could point to, question, and modify a shared external representation. This shift from internalized reasoning to shared inquiry enhanced both individual reflection and collective understanding.

The student-made models thus served as more than individual learning tools. They functioned as what Star and Griesemer (1989) call "boundary objects" – artefacts that can inhabit multiple social worlds and support communication across perspectives. Similarly, David Kirsh (2010) describes such representations as "shared objects of thought" – external structures that make private reasoning visible and negotiable (p. 445). Through these physical models, students engaged in a collaborative process of theory-building, grounded not only in dialogue but in material exploration.

8.3.4 Beyond the flat image

Representations – whether visual or physical – are often created to make complex content more accessible. As Fuhrmann *et al.* (2018) argue, modelling can support students' understanding of complex scientific concepts and help them overcome misconceptions. However, representations do not always function as intended. In some cases, they may even contribute to confusion by reinforcing simplified or overly rigid interpretations. This tension became particularly evident in one workshop where a student worked with Bronfenbrenner's (1979) ecological systems theory, a model commonly visualized as a set of concentric circles. Although Bronfenbrenner himself used the metaphor of Russian dolls, the concentric circle model has become the de facto representation in textbooks and classrooms.

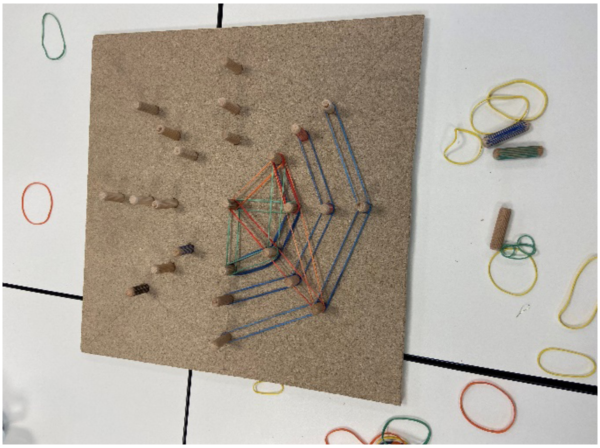

Figure 8.2.
The theory instruments with the concentric circles "re-established".

When students were invited to create physical models of the theory, many instinctively replicated the concentric circle format. Even in the educator-led prototyping sessions, efforts to develop alternative representations were repeatedly drawn back into circular arrangements. In one case, a student re-established the traditional visual model using rubber bands, effectively "correcting" the prototype to match the familiar model (Figure 8.2).

This pattern suggests that some visual models have attained the status of *fait accompli* – what Tim Ingold (2010; 2012) would call *objects*: static and completed forms that resist reinterpretation. In his words, "The object stands before us as a fait accompli, presenting its congealed, outer surfaces to our inspection" (Ingold, 2010, p. 4). When students engage with such representations, they may perceive them as authoritative and complete, leaving little room for reimagining or questioning the structure of the theory itself.

Figure 8.3.
A student's model of the ecological system theory.

However, when these representations are deconstructed and re-assembled through physical modelling, new insights can emerge. In one workshop, a student created a tangible version of the ecological systems theory, which allowed her to physically rearrange the layers (Figure 8.3). This opened a reflective process in which she recognized that the concentric structure may not fully capture the dynamic and overlapping nature of lived experience. The ability to *handle*, *move*, and *reconfigure* elements appeared to offer a deeper engagement than merely *looking at a picture of a model*.

This observation aligns with Kirsh's (2010) concept of "the power of rearrangement" (pp. 446–447) and underscores a key distinction between visual and physical representations. While the former tends to present a finished, often unquestioned form, the latter encourages manipulation, experimentation, and discovery. Physicalizing a model invites students to confront its limitations – not to dismiss it, but to understand that no model can fully encapsulate a theory. In doing so, they develop what Schwarz and White (2005) describe as "metamodeling" competence – the ability to reflect critically on how models represent (and fail to represent) the theories they stand in for.

8.3.5 Focus and flow: immersion in theoretical modelling

During the workshops, several students appeared to become deeply absorbed in the process of building and refining their prototypes. Their attention narrowed, their actions became purposeful and self-directed, and they seemed to lose awareness of time and surroundings. This kind of intense focus is reminiscent of what psychologist Mihaly Csikszentmihalyi (2014) terms a "flow" state – a mental condition in which individuals are fully immersed in an activity, balancing challenge and skill in a way that produces intrinsic motivation and deep engagement. One student expressed it this way: "You don't think about the time because you are so consumed within theory" (Participant 5, Workshop 2). Several of the other students agreed and found it surprising how quickly two hours had passed by. In Workshop 2, one student said: "You just get it visualized in a completely different way than when you have ordinary teaching where you must make your own pictures in your head" (Participant 5, Workshop 2). This points to an important pedagogical insight: if students are already forming mental representations of theory, it makes sense to harness that cognitive activity by externalizing it – bringing the images out of their heads and into the shared space of the classroom. By materializing theory through prototyping, these internal constructions become visible, tangible, and open to dialogue, allowing for deeper engagement and collective reflection. What the student refers to as "ordinary teaching", I would assume, is lectures. If students can enter a state of flow, they are more likely to engage actively with theoretical material, rather than merely reproducing it. A hands-on, workshop-based approach may increase the likelihood of such engagement by supporting immersive and self-directed learning. However, this potential requires further investigation in future research.

8.4 Discussion

The motivation for this study was to explore how theory instruments (Buur *et al.*, 2022) and the act of prototyping might support social work students in developing a deeper understanding of theory. Like most higher education programmes, the social work curriculum is guided by a learning taxonomy – in this case, Biggs' (2012) structure of the observed learning outcome (SOLO) taxonomy, which outlines levels of increasing complexity in student learning outcomes.

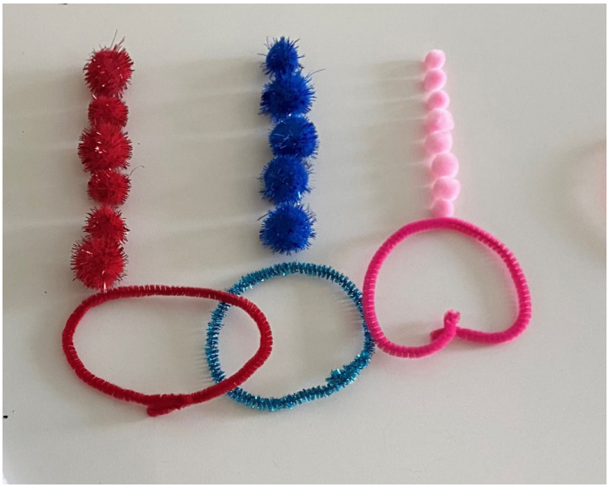

Figure 8.4. Model of Honneth's (2003) theory of recognition.

A central question arising from the workshops is whether the use of tangible tools in teaching can stimulate reflection and thereby support progression toward higher-order learning outcomes. Observations from the first two workshops suggest that students entered the activity with widely varying levels of theoretical understanding. Some participants demonstrated the ability to analyse, compare, and critique theoretical concepts, indicating a relatively high level of abstraction. Others, however, seemed to be grappling with more basic comprehension, resulting in models that reflected a more limited grasp of the theory. This stage of learning, or what Biggs (2012) would classify as "unistructural" in the SOLO taxonomy, is where the student focuses on a single relevant aspect of the task, but lacks an understanding of how different elements relate to each other. At the *pre-structural* level, the student has not yet grasped the task requirements or the theoretical concepts in a meaningful way, while higher levels – *multistructural*, *relational*, and *extended abstract* – involve increasing complexity and integration. An example of a unistructural model can be seen in Figure 8.4, which depicts Honneth's (2003) theory of recognition. In the prototype, the student represents the theory using three isolated objects, each symbolizing a form of recognition: love, rights, and solidarity. While this aligns with the three-part structure described in the literature, the elements are positioned without showing any relation or hierarchy between them. There is no indication of how the forms of recognition build on one another, how they relate to identity formation, or how misrecognition might function as a theoretical counterpoint. As such, the model demonstrates recognition of key terms but not their interconnections, making it illustrative of a surface-level engagement with the theory.

In one case, a student even conflated elements of two separate theories – Bourdieu's (1986) and Putnam's (1995) – and produced a prototype that could be described as *pre-structural*. These examples demonstrate that modelling theory through prototyping is not a shortcut to understanding, nor does it prevent misconceptions. Nevertheless, the workshops showed that even models constructed at a basic or erroneous level often served as useful starting points for reflection and peer dialogue. Misconceptions were frequently challenged and corrected through collaborative discussion with other students, as seen, for instance, in the example above regarding the empowerment model.

It is important to note that none of the students had been asked to prepare for the workshops, for example, by reading specific theoretical texts in advance. This low-threshold approach was deliberate: the aim was to minimize the time and cognitive demands placed on the students prior to participation. I assumed that requiring significant preparation, such as engaging with complex academic texts, might discourage some students from taking part. As a result, students largely relied on memory rather than recent studies. If prototyping were to be implemented more systematically as a teaching method, it would likely benefit from preparatory reading or discussion to ensure a more informed starting point.

Nonetheless, the prototyping process appeared to promote student-centred learning and active engagement – key conditions for deeper learning outcomes (Hoidn & Reusser, 2020). The use of unfamiliar materials and the open-ended nature of the activity may also have contributed to a more accepting climate for feedback. Unlike written assignments or drawings, where a degree of precision is often expected, the imperfection of physical prototypes seemed to signal that tentative or incomplete representations were not only allowed but productive. These imperfections invited interpretation, encouraged dialogue, and opened space for meaning-making in ways that may be less accessible through more conventional forms of expression.

8.5 Conclusion

This chapter has examined how prototyping, understood as a form of theory modelling, can support students in making abstract theoretical concepts more accessible, discussable, and meaningful. Drawing on the notion of theory instruments (Buur *et al.*, 2022), the workshops explored what happens when students are invited to think with their hands and give form to theory through tangible materials. The process did not eliminate misconceptions, nor did it automatically lead to deeper understanding, but it created space for reflection, interpretation, and collaborative meaning-making.

The activity encouraged students to approach theory not as a fixed truth to be remembered, but as something to be negotiated and explored. In this sense, prototyping aligns with Mitchell and Buur's (2010) idea of things to think with in that material artefacts do not just illustrate thought but provoke it. The imperfections and provisional nature of the models seemed to support an open feedback culture, where peer dialogue became central to the learning process.

Although some students found the task unfamiliar and challenging, the workshops indicated that prototyping could contribute to more student-centred and participatory forms of learning. This supports previous research highlighting the value of active involvement in higher education as a driver of deeper learning outcomes (Hoidn

& Reusser, 2020). Furthermore, the findings suggest that physical modelling can make theory feel less intimidating and more flexible – something to engage with, critique, and co-create.

The findings suggest that prototyping may help destabilize rigid perceptions of theory as fixed and untouchable, and instead foster a more active, critical, and relational engagement. However, the approach is not without limitations. Its success depends on context, preparation, and facilitation, and it may not suit all learners equally. Further research is needed to explore how prototyping can be integrated more systematically into curricula and how it affects learning outcomes over time.

Ultimately, the study indicates that thinking through the hands can be more than a creative exercise; it can be a meaningful pedagogical intervention that opens theory to exploration, dialogue, and learning.

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9. Prototyping-as-debate: exploring the situated nature of politics in design

Rose Dumesny, Dorian Reunkrilerk

9.1. Design and debate: discussing the world through politics

Bruno Latour (2022), in his *Compositionist Manifesto*, invites us to conceive of politics as the progressive composition of a common world. For him, pluralism is not an obstacle but the raw material of collective life: “if we put aside what separates us, there is nothing left for us to put in common” (p. 14). Echoing this position, Chantal Mouffe (2005) reminds us that politics is an antagonistic state. The illusion of consensus merely reflects domination, as hegemonic voices impose themselves by excluding others. This suggests that dissensus is the very precondition of discussion and that debate (which, historically, meant both “to quarrel” and “to deliberate”) is central.

Latour (2005) urges us to recognize this antagonism at the heart of an “object-oriented democracy”. Facts, too long presented as neutral, must be re-qualified as *things*: uncertain, heterogeneous, local, and historical entities that, precisely because they divide, also succeed in gathering. Around such things, arenas of speech take shape, whether in official parliaments or everyday scenes where our futures are negotiated.

Badouard, Mabi, and Monnoyer-Smith (2016) identify three regimes of expression that structure these arenas:

> **the regime of critique […] which draws on external sources to legitimize the speaker's intervention ('to render the argument indisputable'); the regime of opinion, which acknowledges a particular point of view ('to make oneself understood'); and the regime of sharing, where the speaker offers personal experience to elicit the audience's empathy. (p. 11)**

Following Latour, we can understand that these regimes can be found well beyond parliamentary chambers: laboratories, temples, marketplaces, and online forums likewise operate as non-dominant arenas where society's collective orientation is sketched out.

9.1.1 Beyond an ornamental politics in design

Adopting a pluralist lens in our everyday micro-political actions raises a question within the design field: how can a design project enact pluralism? How is politics embodied in design, or does it manifest itself? Silvio Lorusso (2024), in *What Design Can't Do*, demonstrates that much contemporary design discourse relies on a stripped-down notion of the political in which the term itself is largely decorative – "The radical slogan, the activist posture, the glorious declaration are adopted as decorations of purely autonomous practices, that is, cut off from the murky waters of micro and macro politics" (p. 220). Lorusso labels this tendency "ornamental politics", a mode of engagement where politics is emptied of material consequence and recast as mere communication. Empty picket lines at festivals (placards flashing vacuous slogans) typify this symbolic stance. The outcome is a design posture in which everything hinges "about what the work says, not what it does" (p. 220).

Yet, design practice has always developed some relation with politics, from William Morris's early reflections through the Bauhaus's social ideals to the provocations of radical Italians. More recently, a field of design has placed *debate* at its core. Critical and speculative design (Dunne & Raby, 2013), reflective design (Sengers *et al.*, 2005), and adversarial design (Di Salvo, 2015) all employ artefacts to expose tacit assumptions, seeking to make visible our unconscious adoption of an object's values while simultaneously inviting audiences to exercise similar critical reflexivity.

Too often, however, these works circulate primarily in galleries, conferences, and journals. As Max Mollon (2019) observes, they "do not encourage people to meet each other, or to meet the author(s), nor do they encourage debate" (p. 116). The risk is the emergence of a closed discursive circle in which critical design projects speak only to the designers themselves: "Removed from practical use, critical design may then become another echo chamber for designers, where they can safely repeat the slogans of design modernism without changing the world" (Ebbesen, 2017, as cited in Lorusso, 2024, p. 239).

Yet, Mollon (2019) underscores that debate is always situated. In his thesis, he develops a model that traces how a critical design project reaches its public by operating within a broader system that interweaves problems, artefacts, media, and audiences. The framework reveals the multiple layers through which debate exerts influence in any given case, from the initial problem definition, through the relative familiarity of artefacts and media, to the channels of communication and the institutions those channels symbolically invoke.

9.1.2 Towards a materiality of politics in design: the role of prototyping

This chapter adopts a concrete, situated, and pragmatic view on debate to move beyond the current abstract status of politics in design practices (whether labelled critical design or otherwise). To do so, we build on insights presented in Dumesny and Reunkrilerk (2023), where we explored prototyping situations as political situations in which power quietly circulates through tools, schedules, and tacit decisions.

Prototyping lies at the heart of design, when a designer's thinking is given material form. Echoing Schön's (1983) notion of a reflective conversation with the situation, prototyping can be seen as a configuration of interdependent diagrams that collectively propel the object under development. A prototype is therefore not a static translation of an idea: it is a series of representational rupture points that steer collective understanding of the project (Bowker & Star, 1999). Vinck (2012) identifies two key effects at stake: a structuring effect that networks actors together, and an alignment effect that crystallizes shared frames of reference. Immediately, political questions arise: Who is invited to the prototype "table", and who remains off-stage? Which materials include, exclude, or empower? How do latent stories, anomalies, or unexpected uses redirect the project?

Our primary interest in the prototype, then, is its ability to connect heterogeneous actors and sustain a dialogic relationship within the project (Yu, Pasinelli, & Brem, 2018). In this sense, prototypes function as boundary objects, whose role is mediation: they offer a stage for deliberation or debate.

In our prior work (Dumesny & Reunkrilerk, 2023), we formulated an analytical framework "to analyse the conditions of a political experience of design within a prototyping situation" (p. 120). This chapter aims to put that framework to the test. By analysing concrete prototyping situations, we explore how designers might sharpen their awareness of the materiality of the debates they orchestrate and thereby weave a political dimension back into everyday design work.

9.2 From an analytical framework to a practical tool

Our previous work allowed us to identify height conditions of a political experience of design within a prototyping situation. To do so, we built an analytical framework from two sets of dimensions linked to a political experience – temporally, based on the three dimensions in the emergence of an arena (*being concerned by a trouble*, *defining a problem*, and *being visible*) and materially, based on the three dimensions for the creation of an assembly (*representing the matter of concern, guaranteeing the representativeness*, and *building the assembly*). Drawing on this analytical framework, we now want to explore its practicality. Therefore, to better identify these conditions, we have associated a pictogram. These pictograms will be used throughout this chapter. We synthesized the seven conditions in Table 9.1, where each is associated with the main dimensions of the analytical framework.

Pictogram	Conditions of a political experience	Short description	Main conditions identified, contributing to the creation of an arena	Main conditions identified, contributing to the creation of an assembly
	Visualizing a situated and dynamic antagonism.	Effective prototyping stems from exposing actors' interests: using real situations as design material and teams map to articulate and explore different subjects, steering discussions throughout each project.	Being concerned by a trouble.	Representing the matter of concern.
	Considering all the voices of people.	Prototyping must let individuals involved in a project voice their personal view of the shared issue, creating diverse spaces and formats that broaden exploration, all steered by a preparatory, representative panel.	Being concerned by a trouble.	Guaranteeing the representativeness.
	Using space as a designing background.	Prototyping should spatialize data collected during a project to allow collage and composition, and clarify whether speech informs, instructs, persuades, or critiques, so every actor recognizes diverse expression modes.	Being concerned by a trouble.	Representing the matter of concern.
	Labelling a thing.	Prototyping translates a "trouble" into tangible causes and liabilities, using diverse formats to reveal its status as a wicked problem, documenting multiple labels of the trouble, and exposing the hidden forces at play.	Defining a problem	Representing the matter of concern
	Using the space as a parliament.	Prototyping spaces must be modular layouts (semicircle, circle, classroom, etc.) hosting dialogues that turn space into a parliament, while immersion over time reveals key moments refining the problem.	Defining a problem.	Building the assembly
	Remaining open to other troubles.	Project communication needs to tailor the description of problems to each audience, using participatory formats that inform and invite action, broadening the scope of the project, and generating new concerns and activities	Being visible	Guaranteeing the representativeness.
	Building the space as an exhibition.	Viewing prototyping as an exhibition requires a co-designed visual identity (during the project) and adaptable spaces that host varied speeches tailored to diverse audience perceptions.	Being visible	Building the assembly.

Table 9.1. Synthesis of the conditions of a political experience, based on our analytical framework (Dumesny & Reunkrilerk, 2023).

In this chapter, we use this framework to create a practical tool, presented in Figure 9.1, that we want to put to the test to understand how design practitioners can engage with the question of politics in their prototyping situations and put their attention on the political

THE HIDDEN ARENA

ANALYZING AND DESIGNING A PROJECT THROUGH ITS POLITICAL EXPERIENCE

1

Use this framework to work on one or more prototyping situations from your project. You can use this framework to imagine a prototyping situation or to recreate a situation you have experienced. First, in the grid below, draw a thumbnail of each situation, focusing on three things:

- First, how the subject of the project is represented and how it changes as new questions are asked during the project.
- Second, how the project brings together people who are themselves sufficiently representative.
- Third, how the situation helps the people in it to talk, argue and make decisions.

2

Identify the different actions presented below that apply to your situation(s) by redrawing the pictograms that match the relevant part of the thumbnail and adding key words.

- Visualizing a situated and dynamic antagonism
- Considering all the voices of people
- Using space as a designing background
- Labelling a thing
- Using the space as a parliament
- Remaining open to other troubles
- Building the space as an exhibition

3

Think about how you can add other conditions (or improve the ones you already have) to help your situations change, depending on how many conditions there are.

How will this help you review how your project is being managed? Do you want to explore more? What about creating different tools?

Make a to-do list of the first actions you would like to put in place:

Figure 9.1.
A practical tool to analyse and design a project through its political experience.

dimension of their daily practices. Therefore, this tool can be used in two ways: downstream of a project to analyse it, or upstream to envision a project that would fulfil a political experience of it. This tool involves a three-step process:

- Represent, in the form of a storyboard, past or future prototyping situations.
- Identify the various conditions within the prototyping situation that could give rise to an arena, using the proposed pictograms and keywords.
- Consider the missing conditions and list possible actions to integrate or emphasize them.

To test our practical tool, we decided to use it on a design project by giving it to a project team. We chose a work in progress because it let us understand how our practical tool could shape the next steps of the project, thus truly putting it to the test. In addition, it allowed us to interact with a team that did not just have a retrospective view of the project, but rather an active and engaged view of the use of this tool.

The tool was tested during two online sessions (two hours each) with some team members (a designer, a facilitator, and a project manager). During these sessions, we asked the team to use the tool while talking to each other. We employed an interactive whiteboard, which let the team draw directly on the tool and add text elements. At the same time, we took notes on what the team added and how they reacted to the tool. In the next sections of this chapter, we will develop our analysis of this use by following the different stages of the tool and identifying its effects.

9.3 Raising awareness on politics in prototyping situations

9.3.1 Initiating another understanding of a project

The chosen use case involves a public-service design project within a French education-policy administration. One of these policies focuses on preparing secondary school students to become future citizens. Since the 1990s, experiencing citizenship has been a key goal of France's national education system. Secondary school is where students learn democratic life and are trained for their role as social actors. Students experience representative democracy: they elect peers expected to voice their concerns within the school, up to *académies*[1] and the ministry level. Yet, this system still raises issues that the project aims to explore. First, few candidates and little involvement from non-elected students in student-life projects are observed. Second, some elected students question the meaning of their mandate, doubting the utility of the role. Finally, elected students need stronger skills in democratic culture to serve as conduits to other students, and better methodological tools.

Note 1.
An *académie* is an administrative grouping together of French schools within a region.

1

Use this framework to work on one or more prototyping situations from your project. You can use this framework to imagine a prototyping situation or to recreate a situation you have experienced. First, in the grid below, draw a thumbnail of each situation, focusing on three things:

• First, how the subject of the project is represented and how it changes as new questions are asked during the project.
• Second, how the project brings together people who are themselves sufficiently representative.
• Third, how the situation helps the people in it to talk, argue and make decisions.

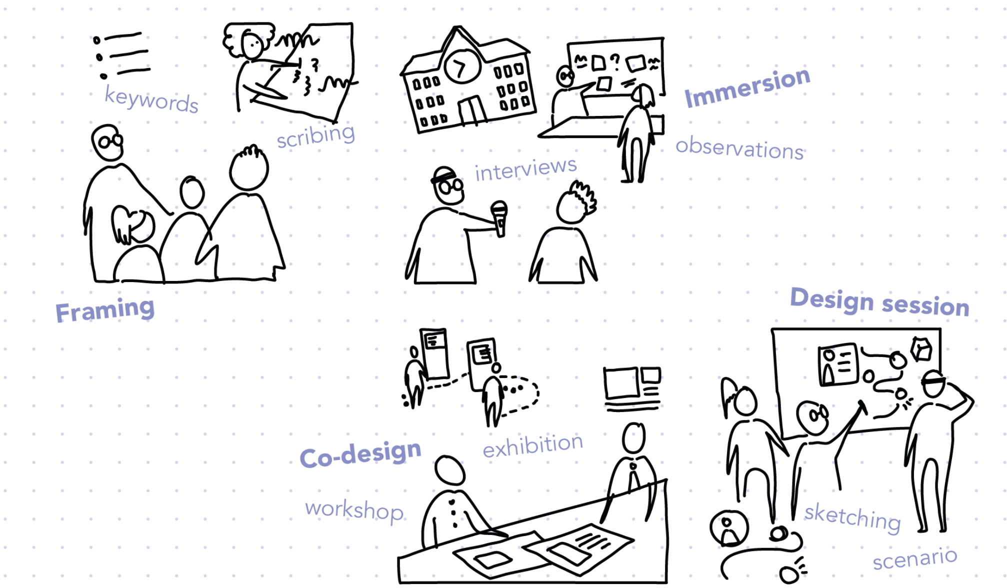

Figure 9.2.
Illustrations of four prototyping situations: from the project scoping meeting bringing together the project team members, immersion sessions meeting students and professionals, to a co-design workshop with teachers, educational advisors, and principals, and finally a design session within the project team.

Building on these issues, the project is now focusing on reinvigorating the school democracy chain by exploring ways to highlight broader forms of civic participation. This is a wider notion than "student life" as it covers engagement inside and outside school. During our test of the tool, the team focused on four prototyping situations already done, each involving different actors at distinct stages of the project (Figure 9.2).

These situations seem to mirror the political dimensions we identified in our previous work, particularly on two challenges:

How people assemble: The project draws in many education actors (students, *académie* advisors, teachers, principals, and even families) who may hold divergent views, practices, and visions. Every prototyping situation must attend to the conditions of its gathering: clarity of the question that justifies it, representativeness of the participants, and the material display of the situation.

A potential arena: Bringing together those directly concerned can create a committed collective to shape a problem spanning multiple issues. For example, does revitalizing school democracy mean inventing new forms or restoring meaning to existing ones, especially representative democracy? Should the project mould the *citizen* envisaged in curricula or spark locally rooted secondary school practices? The project thus mobilizes actors seeking shared and concrete answers.

An interesting observation made during this session was that drawings enabled team members to begin reflecting on their project. Through drawings created by the designer and keywords added by the facilitator and project manager, this clarification exercise enabled team members to express situations by emphasizing aspects they had not fully formalized, such as the diversity of actors, the level of cultural distance between them, the resources used in each situation, and the difficulties encountered when achieving them. This first sequence thus seemed to initiate another level of understanding within the team.

9.3.2 Debating on the political dimension of a project

Once the storyboard of these situations was drawn, the team continued to use the tool by enhancing their drawings with the pictograms and keywords, allowing them to highlight the political dimension of these situations (Figure 9.3).

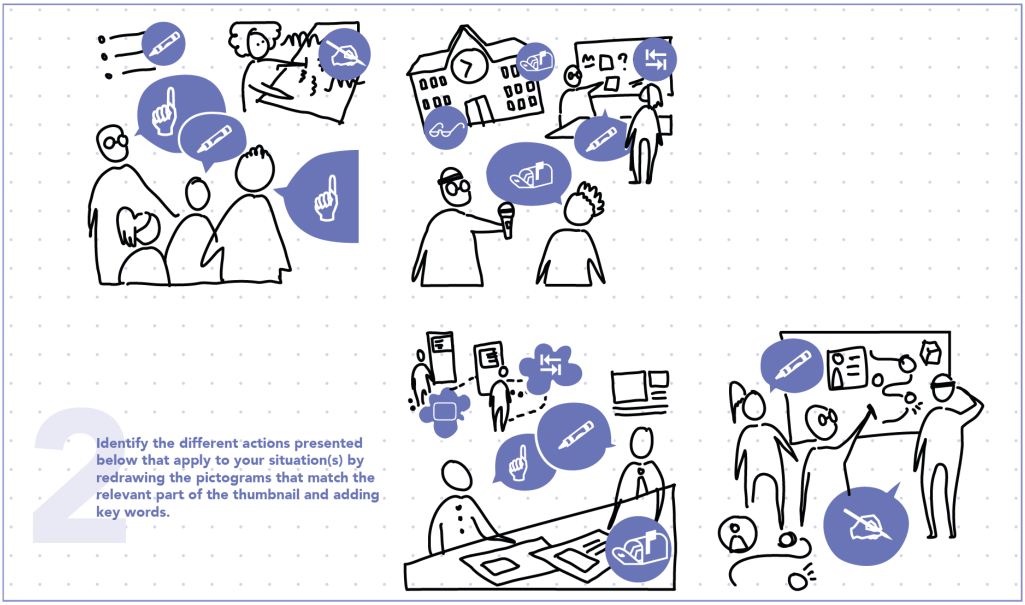

Figure 9.3. Reworking of the drawings: the team identified the conditions already present in each situation, according to their perception. Conditions are represented by pictograms that the tool indicates.

Following that, we detailed this exercise by emphasizing the condition that the team had identified.

Firstly, one of the initial situations was a meeting with the core team of this project to outline the scope of the issues covered by the subject. Part of this team was composed of the administrative office in charge of implementing school democracy. This two-hour meeting was an opportunity to initiate a dialogue on the subject to be addressed by the project (*using the space as a parliament*). The purpose of this meeting was therefore not to gather facts for analysis, but rather to encourage open discussion about the members' concerns (*labelling a thing*). Particular attention was paid to making the words used and their various interpretations visible. To this end, a whiteboard was used as a graphic facilitation. This board played an important role as it allowed anyone to refer to what was being said and to react to a word that had been said previously (*building the space as an exhibition*).

The team then conducted immersions in several secondary schools, ensuring a principle of representativeness by meeting various actors, including elected and non-elected students, educational advisors, and principals (*considering all the voices*). Each immersion day comprised interviews, observations, such as the elected student meeting, and workshops. One such workshop involved elected students drawing a plan of their ideal participation space on a large sheet of paper. The team also conducted sensitive walks around the schools with these same students to better understand how they experienced the school. Another workshop asked all students (*considering all the voices*) to identify topics of general interest they wanted to discuss within their school and to choose an object that they felt was most appropriate for this purpose. The methodology was designed to capture a variety of experiences that would contribute to the initial scope of work (*labelling a thing*) while opening it up to other interpretations (*remaining open to other troubles*). Finally, although frugal, the material elements used seemed to have a direct effect on the students (*building the space as an exhibition*).

Subsequently, a co-design workshop was organized with principals, educational advisors, and teachers, comprising two parts. First, a visit to an exhibition showcasing participatory design projects enabled participants to gently ease into the project theme. During the visit, participants were invited to provide initial feedback using a dedicated form. Then, given the limited number of participants, the group was divided into mixed subgroups to ensure representativeness (*considering all the voices*). Each subgroup was asked to select three projects from the exhibition and imagine how they could be adapted within their secondary schools. This exercise enabled each group to engage in discussions about the conditions for implementing participatory mechanisms, highlighting the important conditions of acceptability to be considered. The team expressed that each subgroup provided an opportunity to discuss different issues related to the team's topic (*labelling a thing*) in a situation of exchange and mutual listening (*using the space as a parliament*).

Finally, the team described a design session held within the team to formulate scenarios. A series of ideation exercises was carried out using creative constraints with basic materials (whiteboard, paper, felt-tip pens). Each production was hung on a wall, allowing the team to refer to an idea brought up during an exercise and keep track of all the ideas (*building the space as an exhibition*). These workshops enabled the team to formalize possible answers to the various questions raised by the project. During this formalization process, the team identified the need to better define each scenario to better target solutions, which led the team to more clearly define the aspects of the problem (*labelling a thing*).

This second stage revealed some observations about our tool. The team had to negotiate the interpretations behind each condition, sharing their understanding. They thus sought to apply the conditions to their situations by explaining various aspects that they felt were relevant. Furthermore, this matching exercise revealed some gaps in terms of conditions. For instance, the team repeatedly observed that *visualizing a situated and dynamic antagonism* was not present. This prompted them to question the absence of certain formats that could have made controversies more visible – especially during immersions. Also, the team emphasizes that *considering all the voices of people* was particularly important given the context of this project and could have been better respected by using different formats for collecting experiences. Finally, the team highlighted the overly linear nature of their approach, emphasizing that alternative, more open participatory design tools would have enabled them to broaden their thinking and explore a wider range of directions, echoing the *remaining open to other troubles* condition.

9.3.3 Enacting other ways of designing a project

The first two uses of the practical tool opened other ways of thinking about forthcoming prototyping situations within the project. Indeed, for the third part of the tool, the project team discussed the next situation: the next stage, therefore, involved a collective work to imagine how the scenario chosen by the team would play out in concrete test situations. The team underlined one constraint: the session must take place online, raising challenges for participant engagement and expression.

Starting from the practical tool, the team identified three conditions and a list of actions that appeared particularly important to make tangible in the forthcoming prototyping situation (Figure 9.4).

The following sections focus on the actions that have been most deliberated within the team.

Using space as a designing background: The selected scenario involves running consultations that engage the entire student body of

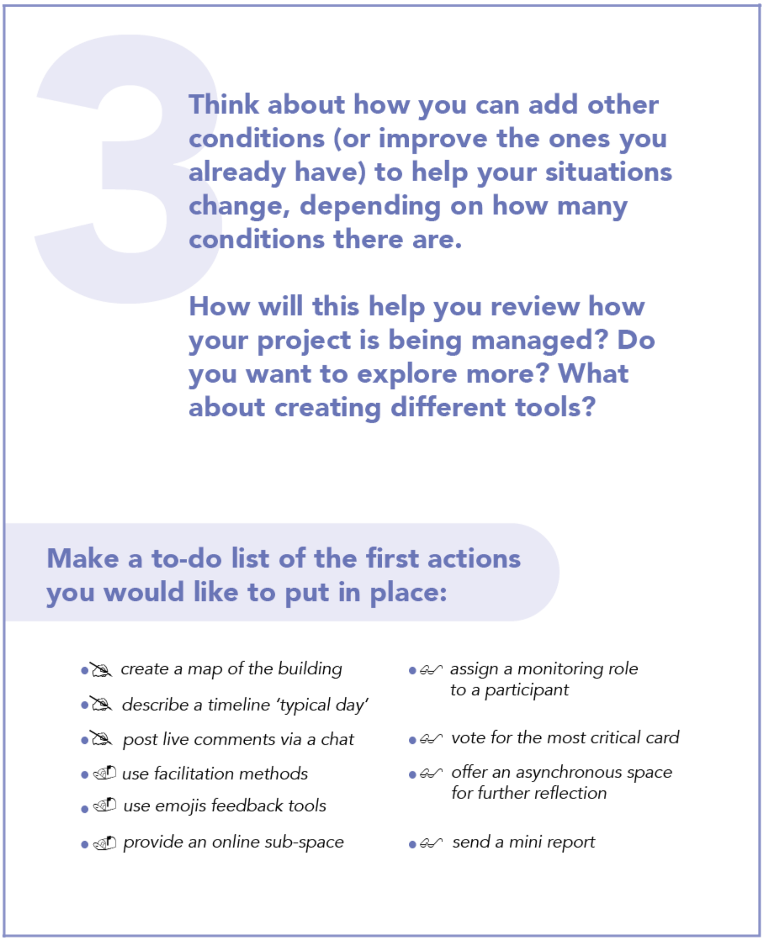

Figure 9.4. List of actions devised by the project team to design their next prototyping situation. Pictograms are used to link an action to a condition.

a school, as well as actors at *académie* level. These consultations will occupy physical spaces (corridors, classrooms, playgrounds, etc.) and temporalities (arrival in the morning, the lunch break, and so on). In an online setting, such spatial and temporal implications can be hard to grasp precisely because the prototyping situation is not situated.

To meet this challenge, several strategies were identified by the team. For instance, each volunteer school could be asked to create a macro map of the building (corridor layouts, rooms, playgrounds) and then add photos or videos that show the rhythms and atmospheres of each place tangible. To deepen this projection into experimentation, participants might create a timeline on the map to mark peaks in participation throughout the school day. This would enable participants to devise a plan tailored to each secondary school, describing a *typical day* in which the scenario unfolds.

Considering all voices: Because the scenario brings together a wide range of actors, the team put the principle of representativeness as important. Yet, online meetings can make expression difficult for some profiles, given existing relationships. For example, interactions between students and teachers differ markedly in a virtual space. Therefore, it was vital for the team not to reproduce behaviours that run against the idea of civic participation.

To tackle this, various facilitation methods were imagined. For example, overall facilitation could be handled by the project team, assisted by two co-facilitators, representatives of the panel (an adult and an elected student). Also, during plenary moments, participants could post comments via an anonymous chat, supplemented by mid- and end-session feedback tools (emojis, for instance) that estimated the sense of listening and expression, allowing facilitators to adjust the activities immediately.

Remaining open to other troubles: The forthcoming prototyping situation may become a catalyst for new ideas, with participants identifying and addressing additional issues not prioritized in the chosen scenario. Yet the purpose here is to work on this scenario in view of concrete experimentation. There is a risk of diverting the session's objective by generating new ideas around new issues. How, then, can openness to other aspirations be maintained?

One option proposed by the team was to provide an online subspace where each emerging idea is traced. To facilitate this, a participant could be assigned a monitoring role, alerting the project team to the recurrence of themes. At the end of the session, participants could vote for the idea they considered most critical. This would invite them to devise concrete micro-experiments within their secondary school, alongside the main scenario. Moreover, to keep the project's possibilities open, an "after-action" channel could be set up, followed by a mini-report.

This final exercise offered valuable insights into the team's approach. Encouraging them to explain the next prototyping situation sparked numerous exchanges within the team, demonstrating the practical application of the tool. Many comments focused on the conditions in which participants could be placed and on exploring the digital tool being considered in more depth. The discursive register thus evolved towards action, reflecting new ideas and desires to be tested (this was particularly evident in the suggestion of integrating participants into the facilitation team). In addition, the team wrote keywords and made other drawings to explain their ideas, revisiting the tool's graphic grammar in the process. At this stage, we observed a different posture within the team, an active posture, engaging the team on their project. In our view, the analytical approach that the team had previously adopted with the tool had enabled them to develop this posture through a shared understanding of the methodological challenges it addressed.

9.4 A reflection-in-action on prototyping-as-politics

9.4.1 A compass to embody debate within prototyping situations

Our test has enabled us to shed light on key points about the practical tool. The two online meetings highlighted the tool's ability to guide the project team through three levels of awareness: a first level highlighting key points in the analysis of their project, which had not been emphasized until now, a second level identifying the shortcomings of the different situations in their project, and a third level of awareness exploring alternatives to their working approach, paying more attention to the deliberative quality of their situations.

In this sense, the tool fulfils a dual purpose. First, it operates as a qualitative evaluation tool, able to reveal political dynamics that quantitative indicators overlook. It thus diagnoses in detail what a project situation has, or has not, produced: the distribution of voices, the materialities mobilized, or the effects of inclusion and exclusion. Second, it can serve as a compass for orchestrating project iterations, guiding the scripting of the next situation by structuring the identification of actors to invite, material formats to mobilize, and feedback mechanisms to establish.

Therefore, testing the practical tool enables the team to work at the *micro-scale* of their practice and focuses on the practical and material dimensions of bringing actors into a debate.

Nevertheless, several limitations must be acknowledged. First, the strong dependence of the tool on context: it must be reinterpreted for every project or risks masking the specific power relations at play. This raises the issue of observational bias: the tool remains vulnerable to the project team's blind spots, which may blunt the analysis's critical edge. Also, it can create a normalizing effect: if reduced to a checklist, the tool could stifle prototyping creativity and weaken the very political dimension. Reflexive and situated use of the tool is therefore essential to preserve its heuristic power. In short, the practical tool acts like a compass: it does not point to the destination but guides designers toward prototyping situations that attend more closely to the politics of spaces, voices, and possibilities. When employed judiciously, it serves to enhance the deliberative quality of a situation. Conversely, when applied mechanically, it risks hiding its potential.

9.4.2 Designing deliberative arenas

By steering designers' attention toward the project *in the making*, this practical tool highlights the importance of the effects generated during a design project. In foregrounding the agency of the project itself rather than its results, the tool affirms the value of the act of designing in its most concrete dimensions, as already analysed by ethnography on design studies (Vinck, 2012). But here, the emphasis is put on prototyping as a means of cultivating a situated politics of design. To refine this stance, we can identify three dimensions that underpin "prototyping-as-politics".

First, by partially materializing possible futures, prototyping situations collapse temporal boundaries between what is and what might be. In so doing, they immediately redistribute the capacity to act, decide, or contest among participants. Each version of a prototype thus prefigures a world in which certain scenarios become tangible while others recede from view.

Second, decisions regarding the properties of a prototyping situation, a particular technology used, or a degree of openness (public vs. private access, etc.) shape who can participate, understand, or influence the project. They privilege actors while marginalizing others with fewer resources or already precarious positions. These decisions unevenly distribute power relations in every prototype.

Third, designers appear less as autonomous authors than as mediators positioned at the intersection of institutional agendas, technical constraints, and civic aspirations. Agency is therefore embedded, negotiated, and contingent within each prototyping situation.

These dimensions allow us to think of prototyping situations as potential deliberative arenas, in line with Mollon's (2019) work on design for debate. In this way, prototyping is a critical activity that reconfigures the collective understanding of a project. This observation foregrounds the reflexive dimension of design practice: designers must attend to the emergence of ideas but also their material conditions, enabling a space for debate.

9.4.3 Contributing collectively to the "lower-case futures"

This view on prototyping as a space of deliberation can guide designers differently in their work, not by prescribing ready-made solutions, but by letting them orient their practice in response to what prototyping reveals *in situ*. At this juncture, Silvio Lorusso's (2024) warning is instructive:

> **After all, design is a compromise with the real, that is, a compromise with past things and, therefore, a negotiation of future ones. To design is both to compromise yourself and to compromise things. Design can undermine reality, while reality can jeopardise design. Against the pseudo-scientific rationale of a project as the result of a logical, ineluctable process, we must opt for a political one, which does not necessarily correspond to activism, but it surely involves a compromise between forces. (pp. 298–299)**

The practical tool we proposed emphasizes the compromise underlying each prototyping situation. Because prototyping creates a conversation between objects and humans with different histories and experiences, it thus does not aim at consensus or dissensus, as proposed by Mouffe (2005). Instead, it institutes compromise at the heart of the situation, among people, emotions, objects, and perceived realities.

> **The design field should be considered a political entity, but not because it regularly issues statements and manifestos. It is political**

> **because it is concerned with its own organisational politics, as well as the politics of the artefacts it circulates. Such a design field would be preoccupied with tangible, lower-case futures. (Lorusso, 2024, p. 303)**

Through our test, we could note the beginning of an agency where the tool let the team pay attention to the organization of the politics of their work. However, this cannot be attributed solely to the tool, and we must consider the overall situation in which this test was carried out. It seems important to question the influence of our presence when using this tool: to what extent were we able to influence our observations? To what extent can we consider this tool a "stand-alone tool", functioning without dialogue with an external third party, and an external third party who is not a peer? We consider this observation to be important because it suggests that this work could represent an opportunity for peers to meet, beyond design discourses, by working collectively on our practices. Consequently, this tool potentially engages in a process of encounter, which could bring together other designers to create common interests around things, as suggested by Latour, or even a deliberative arena within the design community concerned by the "lower-case futures".

9.5 Conclusion

This chapter raises questions about how prototyping can stage situations that allow experiencing politics in design. The practical tool we tested exhibits distinct material qualities, prompting different modes of speech, of assembling, of voicing concerns, of deliberating, and of designing. Hence, by putting forward this tool, we encourage design practitioners to treat it as a way of entering into a wider dialogue with themselves about their day-to-day practice and the situated nature of politics.

Therefore, this work prompts a renewed attention to everyday work environments in design. When designers immerse themselves in a given situation, how can they stimulate the political vitality of that milieu? Conversely, when classification systems remain invisible

(Bowker & Star, 1999), how might designers cultivate conditions for their questioning? Hence, equally important is the capacity to render the invisible visible: when tacit classification systems remain unquestioned, designers should cultivate formats that invite debate rather than closure.

By grounding politics in the act of prototyping, we invite practitioners to stage arenas where compromise surfaces. In so doing, they not only reflexively enrich their practices but also contribute to broader, material debates about the "lower-case futures" we collectively build on a daily basis.

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PART 4

Developing the design process through prototyping

10. Rethinking assistive technologies through hybrid manufacturing: a case study on designing for amyotrophic lateral sclerosis (ALS)

Yash Bohre, Purba Joshi, Rowan Page

10.1 Introduction

Assistive technology (AT) encompasses a wide range of devices, equipment, and systems designed to support individuals with functional limitations. The World Health Organization (WHO) defines AT as an umbrella term covering assistive products and their related systems and services that “enable and promote the inclusion, participation and engagement of persons with disabilities, ageing populations and people living with chronic conditions” across all societal domains (Global Report on Assistive Technology, 2022).

AT spans over a broad spectrum, from low-tech solutions such as crutches, wheelchairs, and reading glasses to high-tech innovations, including exoskeletons, speech generation devices, and robotic feeders. This technology extends beyond personal devices to include environmental modifications, such as portable ramps and grab-rails that enhance accessibility in various settings. While these are primarily designed for people with disabilities, their benefits extend to a broader population. For instance, curb cuts initially intended for wheelchair users benefit parents with strollers and travellers with luggage. Similarly, jar openers created for individuals with arthritis prove helpful for anyone struggling with tight lids. Globally, it is estimated that 15% of the population, i.e., over one billion people, experience some form of disability, with approximately 2–4% facing severe functional limitations (Chan & Zoellick, 2011).

The need for AT is substantial and growing. Current estimates suggest that 2.5 billion people need assistive devices worldwide, with two in three adults over 60 requiring at least one such device (Chan & Zoellick, 2011). As global populations age and the prevalence of noncommunicable diseases increases, this figure is projected to rise to 3.5 billion by 2050. Based on self-reported survey data published by WHO's Global Health Observatory, modelled estimates indicate that 31.3% (uncertainty limits: 25.7% to 36.9%) of the global population needs assistive products, including spectacles, while 11.3% (8.8% to 13.9%) need assistive products excluding spectacles (*Global Report on Assistive Technology*, 2022).

Despite their potential to significantly improve daily functioning, many assistive devices face barriers to widespread adoption, particularly due to systemic issues across their design, production, and delivery lifecycles. One critical concern is the high abandonment rate: studies report that nearly one in three assistive devices is eventually discontinued by users (Phillips & Zhao, 1993). Several barriers prevent AT from realizing its full potential. These barriers can be categorized into four primary domains: (a) access to the device, (b) lack of user input, (c) failure to accommodate evolving symptoms, and (d) lack of design for dignity.

10.1.1 Access to the device

Affordability consistently emerges as the most significant barrier to accessing assistive technologies, followed by a lack of support services and limited availability. As the Assistive Technology Industry Association (ATIA) acknowledges, the effectiveness of assistive devices often depends on correctly matching individual needs and preferences, yet access remains constrained by economic and geographic factors. This is strongly supported by a scoping review conducted across the WHO European Region, which found that barriers to access AT are consistently linked to accessibility, affordability, and acceptability (Mishra *et al*., 2024). Their study reveals considerable disparity in needs for the technology being met, with visual and hearing impairments receiving better coverage up to 87–90% compared to communication and cognitive impairments as low as 10–60%. A comprehensive study on complex rehabilitation technology (CRT) identified varied funding sources across 21 countries, highlighting how financial structures significantly impact service delivery (Betz *et al*., 2022). Their research reveals that inconsistent funding mechanisms create substantial barriers to accessing appropriate mobility devices, reinforcing the argument about economic constraints.

10.1.2 Lack of user input

The effectiveness of assistive devices often depends on correctly matching individual needs and preferences; the involvement of relevant stakeholders is significant for the adoption of a device (Boyle *et al*., 2022). Research demonstrates that what works for one person may not work for another, even with similar functional limitations. Devices that are selected without adequate user involvement are significantly more likely to be abandoned, with abandonment rates as high as 29.3% in a study of 227 adults with disabilities (Phillips & Zhao, 1993). Their study also reported that mobility aids are most frequently discarded due to a lack of user input in selection and changing user needs over time. A survey of AT design found that up to 30% of all devices are abandoned within a year, causing negative impacts on users. This study examined the intersection of occupational therapy and design thinking, concluding that collaboration between these disciplines significantly improves products and reduces abandonment issues. The importance of user input is further emphasized in a systematic review focused on participatory co-design with older adults, which identified key mechanisms of mutual awareness, mutual learning, trust, and reciprocity as essential factors in the successful development of AT (Carroll *et al*., 2021). The authors concluded that "participatory co-design requires a restructuring of power relations between end-users and those traditionally in control of technology design".

10.1.3 Failure to accommodate evolving symptoms

Studies on assistive technology abandonment reveal rates ranging from 29.3% to 70%, influenced by various factors, including the inability of devices to adapt to changing user needs (Phillips & Zhao, 1993). A meta-review of 40 published papers (Howard *et al.*, 2022) identified key challenges hindering effective adoption and sustained use of assistive technology among individuals with chronic health conditions. Their findings highlight limitations in design and functionality, where devices often fail to accommodate users' evolving needs as their conditions improve or deteriorate. This issue is particularly pronounced when health conditions change (i.e., improved or deteriorated), making the product less relevant or incompatible with current needs (Sugawara *et al.*, 2018). A systematic review by Boyle *et al.* (2022) examined promoters and barriers to AT implementation, highlighting the importance of flexible, adaptable design.

10.1.4 Lack of design for dignity

Psychosocial factors significantly influence assistive technology acceptance and continued use. The psychosocial impact of assistive devices scale (PIADS) validates that factors such as self-esteem and adaptability are critical retention drivers, with low scores predicting discontinuation (Demers, 2002). Social stigma and aesthetics also lead to device abandonment, as users may feel embarrassed or self-conscious using assistive technology that is visibly different or bulky. Furthermore, some users prefer alternative strategies that preserve their sense of independence and control, reflecting the importance of user autonomy in assistive technology design and implementation (Sugawara *et al.*, 2018). A comprehensive review identified 16 broad categories of assistive technologies with 37 specific technologies for elderly populations (Pramod, 2023). Their analysis of 112 academic articles emphasizes how design considerations play a vital role in effective use of AT, particularly addressing dignity and stigma concerns

Conditions marked by progressive or evolving symptoms often see higher rates of assistive device abandonment. As individuals' physical capabilities change, either due to deterioration or improvement, their devices must adapt accordingly. However, most commercially produced devices lack the flexibility to accommodate these shifts. This limitation is rooted in the standardized nature of mass-manufactured devices, which are typically designed to meet the needs of a broad demographic with shared symptoms rather than tailored to individual variations. Designing general-purpose products involves negotiating trade-offs between competing priorities like function, cost, and manufacturability. In engineering terms, this balancing act is often referred to as optimization (Ravi, 2020), but it frequently comes at the cost of individual fit and usability.

Addressing these limitations requires rethinking how assistive devices are designed and produced. Alternative approaches, such as participatory design, skilled craftsmanship, DIY innovation, and digital fabrication, offer promising pathways. Many users, facing the inadequacies of mass-market devices, adapt or customize their tools to better meet evolving and highly personal needs (Hurst & Tobias, 2011). Yet, these grassroots methods come with constraints. For example, while digital fabrication allows for greater personalization, the materials used in at-home prototyping are often unsuitable for prolonged wear, particularly where biocompatibility and durability are critical (Hofmann *et al.*, 2016; McDonald *et al.*, 2016). Additionally, barriers such as limited access to prototyping equipment like 3D printers or computers and insufficient training in CAD tools restrict the uptake of these methods among many potential users (Hofmann *et al.*, 2019). Even when access is available, a lack of confidence or experience often deters individuals or caregivers from independently developing customized solutions (Hook *et al.*, 2014).

Building on insights from our conference publication (Bohre *et al.*, 2023), this chapter takes a broader, more reflective view of hybrid manufacturing as a method for developing assistive technologies for progressive conditions like amyotrophic lateral sclerosis (ALS). While the earlier work primarily described the design and prototyping phases, the current chapter extends that discussion by examining how hybrid approaches can support context-specific, adaptive, and socially dignified interventions. It incorporates additional learnings from longitudinal fieldwork, user testing, and stakeholder collaboration, offering a more comprehensive account of the design process and its implications for localized AT innovation.

Among the populations most affected by poorly fitted assistive technologies are individuals diagnosed with Motor Neuron Disease (MND), particularly its most common form – ALS (Kiernan *et al*., 2011). ALS is a progressive neurodegenerative disorder that impairs voluntary muscle control by gradually disrupting neural communication between the brain, spinal cord, and peripheral nervous system. It manifests through muscle weakness, atrophy, and a loss of motor function in the limbs and torso, significantly impacting everyday activities such as walking, speaking, and eating. With no known cure, assistive devices become essential tools in maintaining functional independence. However, the role of such technologies changes as the disease progresses. In early stages, devices may help delay muscular decline, while in later stages they are relied upon to restore or support daily functions (Connors *et al*., 2019; Sane & Sharma, 2016). This evolving need profile makes standardized solutions inadequate, as they rarely accommodate the nuances of individual trajectories. Mass-manufactured products are designed for homogeneity, prioritizing cost-efficiency and scalability over adaptability. These systems are not equipped to handle the demands of bespoke fit or functional personalization. Therefore, exploring alternative fabrication approaches becomes essential, ones that can accommodate variations in design and components and allow for continuous iteration based on the user's changing condition.

Hybrid manufacturing presents a promising solution for producing assistive technologies that require customization and modularity. By integrating multiple fabrication techniques, such as traditional handcrafting with digital tools like 3D printing, this approach leverages the strengths of each method to compensate for the weaknesses of the other. For instance, industries like jewellery-making have successfully adopted hybrid workflows, where digital modelling accelerates complex detailing, while casting and finishing are still performed by skilled artisans. This fusion of digital and manual processes reduces production time, enhances precision, and lowers costs, making it an adaptable strategy for low-volume, high-variation products (Mahal & Karan, 2009).

In India, the growing demand for medical and assistive devices has outpaced the availability of suitable, affordable solutions through mainstream supply chains (Kang & Ma, 2017). Limited access to standardized products and their high costs have contributed to the rise of an informal sector focused on handcrafted assistive devices. While these locally made solutions often succeed in addressing urgent needs affordably, they fall short of meeting clinical standards, as there is no formal regulatory oversight (Mahal & Karan, 2009). Local fabricators often demonstrate impressive problem-solving and craftsmanship, particularly when responding to individual user needs. However, they typically lack access to precision tools and clinical data required for complex medical components. For example, accurately shaping a prosthetic socket demands high-resolution scanning or moulding of the residual limb, capabilities that are often out of reach. Therefore, this project aimed to enhance local makers' capabilities by introducing digital fabrication tools such as 3D printing. The goal was to co-develop a bespoke assistive solution for ALS users by combining community-based skills with accessible prototyping technologies.

This project adopts a design-centric and practice-based research approach to address a critical gap in the current AT landscape: the lack of adaptive, dignified, and contextually appropriate solutions for people with progressive conditions such as ALS. Grounded in real-world constraints and user experiences, the study focuses on the collaborative development of an assistive footwear that supports users experiencing foot drop, a common and mobility-limiting symptom of ALS. By engaging with end-users, caregivers, clinicians, and local fabricators, the project explores how hybrid manufacturing, combining rapid prototyping techniques like 3D printing with skilled local craftsmanship, can create bespoke assistive devices that are both functionally effective and socially acceptable.

This chapter examines the following research question: How can hybrid manufacturing methods support designing and prototyping contextually relevant, adaptive, and aesthetically dignified assistive technologies for individuals with ALS?

To address this, we present a detailed case study of an assistive footwear's end-to-end design and fabrication process developed through an iterative, participatory design methodology. The following section outlines the methodological framework and participatory design process used to engage stakeholders, define user needs, and prototype the assistive device through hybrid manufacturing.

10.2 Methodology

This section presents hybrid manufacturing not merely as a fabrication strategy but as a guiding methodological stance that informed the design of an assistive footwear device for individuals with ALS. In this context, “hybrid manufacturing” encompasses blending digital and manual techniques, formal clinical knowledge and informal craft expertise, and participatory engagement alongside iterative technical development. It reflects the complex terrain of designing assistive technologies in a low-resource setting, where material constraints, evolving user needs, and distributed knowledge systems require a flexible and responsive design approach.

10.2.1 Framing hybrid manufacturing as a methodology

This project approached hybrid manufacturing not just as a production method, but as a way to structure the overall design process. By hybrid, we refer to combining digital fabrication tools like 3D printing and CAD modelling with local craft practices such as shoemaking. We also refer to hybrid as the collaboration between clinical experts, informal makers, and people with ALS. This approach was necessary because of the nature of ALS, where symptoms evolve over time and no two users have the same progression. As a result, the design process could not be linear or fixed; it had to stay flexible and responsive to individual needs.

The Indian context adds another layer of complexity. Access to standard assistive technologies is limited by cost, availability, and the lack of fit to local environments. While low-cost solutions exist, they often do not meet medical or user requirements. In this situation, we needed to work with what was available while aiming for safety, comfort, and dignity. Hybrid manufacturing allowed us to bridge this gap by combining the precision and repeatability of digital tools with the contextual knowledge and adaptability of skilled local makers.

This approach also meant working across different forms of knowledge. Clinicians brought an understanding of the biomechanics and progression of ALS. Users shared their lived experiences and needs. Makers understood materials, wearability, and local production constraints. As researcher-designers, we had to move between these spaces and translate ideas. The prototyping process was not just about building devices; it became a way to have conversations, test assumptions, and learn what mattered most.

10.2.2 Social hybridity: working with users, clinicians, and informal makers

The design process involved close collaboration with diverse stakeholders, each bringing different kinds of expertise to the table. These included people living with ALS, clinicians, caregivers, and informal shoemakers. Their inputs were not limited to a single phase of the project; they were actively involved throughout the research, from identifying the problem to testing the prototype. Working with such a mix of formal and informal actors required a different kind of design practice, one that was open to negotiation, translation, and learning across domains.

The initial interviews with people diagnosed with ALS helped frame the direction of the project. While the clinical diagnosis and the amyotrophic lateral sclerosis functional rating scale-revised (ALSFRS-R) scoring helped understand the medical condition, it was the lived experiences of users that helped identify foot drop as a critical issue. The ALSFRS-R is a 12-item questionnaire used to assess the functional abilities of individuals with ALS (Cedarbaum & Stambler, 1997). Several participants shared how they struggled with walking, fell often, or avoided going out due to the risk and embarrassment. These conversations shifted the project's focus from general mobility to a more targeted intervention. One user mentioned, “I tried using an AFO, but it was too bulky; I couldn't wear it to work.” This kind of feedback gave direction to the design brief.

Clinicians contributed by helping us understand the mechanics of foot drop, the progression of symptoms, and the risks of injury. Their feedback was essential in ensuring the design did not compromise safety. They also helped us identify the stages of the disease where assistive footwear could offer the most benefit. In later phases, clinicians reviewed the prototypes and suggested adjustments to strap placement and arch height based on their understanding of muscle strength and joint movement.

Working with informal shoemakers brought another layer of learning. We identified local shoemakers in Mumbai who had experience with custom footwear, though not necessarily for medical needs. Figure 10.1 shows the workshop of the local shoemaker. Their understanding of materials, fit, and comfort was vital in converting the digital prototype into a functional product. They also guided decisions around which outsoles to use, how to stitch or bond parts together, and what kinds of fabrics would hold up in Indian weather. While they did not use technical vocabulary, their knowledge was deeply embedded in practice.

Bringing together users, clinicians, and makers meant constantly translating between different ways of speaking and thinking about the problem. For example, what a user described as “discomfort” might be interpreted by a clinician as a pressure point, and by a shoemaker as a fabrication flaw. As the researcher-designer, we often acted as a bridge, making sketches, modifying CAD models, or adjusting language to ensure everyone remained part of the conversation. This

Figure 10.1. Workshop setup of the local shoemaker.

way of working was slower but more grounded. It allowed the design to stay close to the everyday realities of users, while also ensuring clinical and functional appropriateness.

The social hybridity of the process was not just about inclusion; it was about co-creating a design process that could respond to different forms of expertise. Each stakeholder shaped the project in meaningful ways, and the final outcome was only possible because of this collective effort.

10.2.3 Material hybridity: negotiating technologies, tools, and constraints

The prototyping process involved working with multiple materials and manufacturing techniques, many of which had to be adapted based on availability, cost, and usability. We started by exploring industrial-grade materials like polyamide 12 (PA12), commonly used in orthotic applications due to its strength and flexibility. However, these materials required access to high-end equipment like selective laser sintering (SLS) or multi jet fusion (MJF), which were not accessible within the scope of this project due to high cost and limited local availability.

Instead, we focused on materials and tools that were locally available and could be used in iterative prototyping. Flexible polylactic acid (PLA) became a practical choice. While not medically certified for long-term use, it allowed us to rapidly 3D print multiple versions of the heel arch using fused deposition modelling (FDM). We used Autodesk Fusion 360 to model the part and explored different parameters like wall thickness, infill, and print orientation to ensure both flexibility and strength. The arch was designed with a slight inward bend (Figure 10.2A) to provide natural tension when worn, and mounting points were added to integrate it with straps (Figure 10.2B) and the shoe body.

Each design iteration taught us something new, not just about form and function, but about printability and failure points. For instance, we learned that printing the arch perpendicular to its bending plane improved its durability, while printing it flat reduced support material and made the finish cleaner (Figure 10.2C). These adjustments were based on trial and error, often guided by conversations with local fabricators who had experience working with similar materials in other contexts. Beyond the printed component, material choices extended to the rest of the shoe. The outsole needed to be flexible enough for walking but stiff enough to support the arch insert. Local shoemakers helped us identify options that were durable, lightweight, and compatible with the custom component. For the inner lining and straps, we selected breathable, non-stretchable fabrics that were comfortable to wear and easy to clean. The straps also had to provide enough tension to lift the forefoot without causing discomfort or slippage.

In short, the material selection process was not about choosing the best material in theory, but the best option within given constraints. Each decision had to balance durability, comfort, manufacturability, and user acceptance. Hybrid manufacturing gave us the flexibility to experiment with combinations that would not have been possible in a traditional production pipeline. It also allowed us to make and test prototypes quickly, respond to feedback, and adapt without starting from scratch.

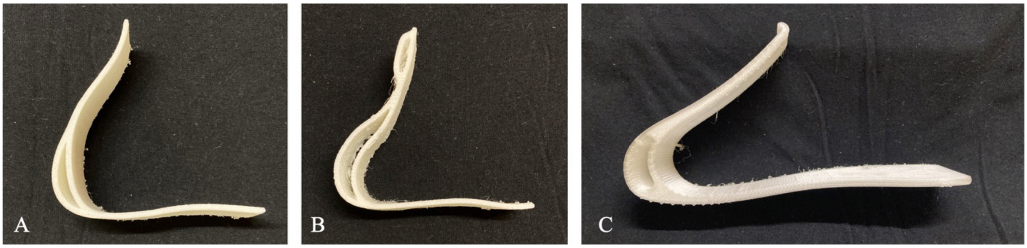

Figure 10.2.
A: 3D printed heel arch.
B: heel arch iteration with strap mounts and pre-tension.
C: 1:1 scale prototype of the final heel arch 3D printed in flexible PLA to be fitted in the shoe.

10.2.4 Iterative prototyping as reflective practice

Each iteration of the prototype was treated as a learning opportunity, an entry point to reflect, adapt, and reframe both the design and the assumptions behind it. The first version of the footlift shoe was developed based on user interviews, clinical inputs, and early sketches (Figure 10.3A). The heel arch was modelled in Fusion 360 and printed in flexible PLA, while the rest of the shoe was assembled by a local shoemaker. We assumed that this configuration would lift the forefoot effectively, but the first round of testing quickly revealed its limitations.

When the first user (U1) tested the shoe under clinical supervision (Figure 10.3B), the arch did not provide enough lift. The straps, though secure, were not placed in a way that properly supported the ankle. The outsole was too soft, which reduced the rebound effect we were aiming for. These issues were not apparent in CAD models or during static assessments; they emerged only during real-world use. Clinicians observing the test noted specific biomechanical concerns, such as insufficient mid-foot support. Their feedback was precise, but what stood out equally were the comments from the user: "It's better than before, but I still can't walk with confidence. I feel like my foot is dragging".

Instead of treating this feedback as a failure, it became the starting point for a new iteration. We used temporary straps to test alternate positions before printing a new version of the arch (Figure 10.3C). Since the base CAD model had already been parameterized, making changes like increasing the arch length or adjusting the mounting points took very little time. The second prototype was printed, assembled, and delivered by a different shoemaker, who followed the instructions from the earlier iteration. This version showed noticeable improvements: the arch provided better lift, the straps held the foot in place, and the shoe felt more stable (Figure 10.3D).

To validate the improvements further, we tested this version with a second user (U3) who had a different foot size and anatomy. The results were promising, the arch adapted well, and the core mechanism remained functional across sizes. This flexibility reinforced the idea that the device could be scaled or modified for different users with minimal redesign. The feedback also confirmed that the design could

Figure 10.3.
A: final functional prototype.
B: testing the prototype with U1.
C: testing with the modified position of straps.
D: testing of the second prototype.

be adjusted not only for different stages of ALS but also for different gendered, anatomical and cultural expectations around footwear.

By using prototyping as a form of reflection, we were able to move beyond a static understanding of user needs. The process became a conversation between the digital model and the physical world, between the user's feedback and the maker's skill, between clinical accuracy and lived experience. Prototypes were not endpoints; they were tools to reveal what still needed attention. In that sense, each prototype helped clarify the next question rather than answer the last one.

10.2.5 Towards a situated, scalable model

While the prototype developed through this project was tailored to the specific needs of individuals with ALS, the broader aim was to explore whether such a design approach could be applied more widely. Hybrid manufacturing, by combining digital tools with locally available skills and materials, proved to be not only feasible but also adaptable. The final prototype (Figure 10.4) was not just a finished product in the conventional sense, but a proof of concept for a model of designing and producing assistive technologies that are situated, responsive, and scalable.

Figure 10.4. Pre-production version of the AFO shoe.

Situated, in this context, refers to how design decisions were shaped by real-world constraints: the limited availability of certified materials, the knowledge of local shoemakers, the informal networks used to source components, and the lived experiences of users and caregivers.

These were not obstacles to be designed around; they were conditions to be designed with. Every aspect of the process, from material selection to prototyping workflows, had to make sense in the context of local infrastructure, expertise, and needs.

At the same time, scalability was built into the process, not through mass production, but through modularity, documentation, and repeatability. Once the digital files were refined and the assembly process was documented, it became possible to reproduce the shoe design using different combinations of materials and with different makers. In fact, the second prototype was built by a different shoemaker who was briefed with sketches and part instructions and was still able to assemble a functionally identical shoe in under five hours. This kind of reproducibility, supported by minimal tooling and local materials, opens up possibilities for small-scale, distributed manufacturing of assistive technologies.

This approach does not compete with high-end medical devices but fills a critical gap between standardized mass-market products and one-off DIY fixes. It offers a middle ground, one where design is collaborative, fabrication is decentralized, and solutions can be adapted as user needs change. As progressive conditions like ALS require devices that evolve over time, hybrid manufacturing offers a way to keep the process of making open and responsive.

Rather than seeing this methodology as a one-off intervention, we see it as a working model that can be extended to other conditions and communities, especially where access to personalized assistive technology is limited. The methods, tools, and relationships developed here can be adapted, reconfigured, and scaled, not through economies of scale, but through networks of care, craft, and contextual knowledge.

10.3 Discussion

This case study demonstrates how hybrid manufacturing, when embedded within a participatory design process, can serve as an effective means for prototyping bespoke AT for progressive conditions such as ALS. Rather than relying solely on institutional production or informal DIY fabrication, this approach strategically combines digital precision with local craft expertise to create assistive solutions that are functionally adaptive, socially acceptable, and contextually manufacturable.

A key contribution of this project lies in advancing a repeatable design-to-fabrication workflow that bridges the gap between end-user needs, clinical priorities, and the capabilities of local skilled makers. The use of 3D printing enabled rapid, iterative prototyping of structurally sensitive components (like the heel arch) while local shoemakers provided valuable knowledge around materials, comfort, climate-appropriateness, and durability, such insights often overlooked in lab-based fabrication. The resulting prototype was not only functional but also dignified in appearance, which participants noted as essential to long-term use and social confidence.

Several design tensions emerged during the process. One was between bespoke fit and modular reuse, while the arch was customized for one user (U1), it proved partially effective for others (e.g., U3), suggesting a possibility for modular standardization in future iterations. Another tension involved craft versus clinical compliance: while local makers possess valuable skills in fabrication and repair, they often lack access to medical-grade materials or biomechanical data, pointing to a need for supportive infrastructure, training, or certification. Additionally, we navigated a trade-off between speed and rigour; the ability to quickly iterate using flexible PLA and FDM printing was invaluable, but long-term durability, skin safety, and compliance still require clinical validation and further material studies.

From this process, we derive three design principles that may be applicable to similar AT contexts:

1. *Design for disguise*: Assistive technologies that resemble everyday objects (e.g., shoes) help reduce stigma and enable social confidence.
2. *Fast-to-fit modularity*: Separating standard and custom components allows reuse, iterative design, and faster deployment across varying user needs.
3. *Embedded local knowledge*: Involving craftspeople in the production process leverages contextual expertise that is critical for usability, comfort, and environmental fit.

These findings speak directly to the systemic challenges identified earlier, including high abandonment rates and a lack of contextual responsiveness in AT design. By foregrounding user dignity and adaptability, this case contributes to broader conversations in assistive technology research and policy, particularly around distributed production models, care system decentralization, and the co-production of health technologies. In the Indian context, where formal AT supply chains often fall short, this model illustrates the potential for locally embedded, globally informed innovation: not as a stopgap, but as a viable long-term strategy for responsive, personalized care.

10.4 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 undergoing long-term usage testing. 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 such devices that meet the AT requirements of people with individualized 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.

As the global demand for assistive technologies continues to rise, particularly in ageing and low-resource populations, there is a growing need to explore alternative design and production approaches that can offer timely, personalized support. This project demonstrates how hybrid manufacturing can support the development of context-specific, user-informed devices for people with ALS, whose needs change rapidly and differ widely between individuals.

By integrating digital fabrication tools with local craft knowledge and clinician input, we were able to design and prototype a functional, discreet, and adaptable foot-lift shoe. The project shows how accessible tools like FDM printing can complement the skills of informal makers to deliver solutions that are both technically sound and grounded in everyday reality. The process enabled faster iteration, more meaningful stakeholder involvement, and higher responsiveness to evolving user needs.

This remains an ongoing project. Long-term usage testing is underway, and future plans include clinical validation and the development of a replicable design framework. The goal is not only to bring the product closer to market but also to document a methodology that other designers, rehabilitation teams, and grassroots makers can adapt for different conditions and communities.

Ultimately, the project highlights that designing for progressive conditions requires more than just technical solutions; it requires methods that are flexible, situated, and collaborative. Hybrid manufacturing, when practised in this way, offers a promising route for building more inclusive, adaptive, and sustainable assistive technologies.

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11. A virtual reality experiential prototyping tool for the application of anthropometry in complex, confined human environments

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11.1 Introduction

Designing complex confined human environments requires a rigorous application of anthropometry to accommodate the full range of body sizes within the target population. Although gathering and analysing data for anthropometry is well-established, the tools and methods to apply the data for design are not as advanced, particularly in the early stages of design when the application of anthropometry will have the greatest impact. Key tools include physical models and digital human manikins (DHMs) used in computer-aided design (CAD) and ergonomics software. Currently, DHMs must be posed segment by segment, which is cumbersome, time-consuming, and requires expertise, inhibiting their use throughout the design process. These challenges reduce the effectiveness of DHMs in the design process.

The real anthropometric experience system (RAES) addresses these limitations by offering a new way to prototype with DHMs. It provides designers with a physical experience of various body sizes, leading to a more empathic understanding of the environment for different users. It also enables quick, realistic DHM posing for use in early-stage design development. The system includes two tools: a DHM poser and a virtual reality (VR) environment. In the poser tool, users move in front of a motion capture device while viewing a screen showing a DHM driven by their movements. Users can pose DHMs of different body sizes and export these poses to CAD. In the VR tool, designers enter a virtual environment from a DHM's viewpoint, experiencing different body sizes physically and visually, enhancing empathy and understanding.

This chapter describes new prototyping methods and tools for applying anthropometry in design. It outlines the human-centred design (HCD) methods for the application of anthropometry, developed at the Studio for Complex Human Environment Design (SCHED) for designing habitable spaces in isolated confined environments. The chapter examines the limitations of current prototyping tools and methods, highlighting their challenges, barriers for use early in the design process, and the lack of experiential richness. To address these issues, new design methods and tools using body motion tracking and virtual environments were developed. These innovations offer new methods for using DHMs early in the design process, enabling empathetic insights into the physical experiences of various body sizes.

11.2 Anthropometry and design for isolated confined environments

11.2.1 Applying anthropometry

When designing a product, clothing, or environment, it is crucial to size the item to suit the range of body sizes in the user population. Anthropometry, the science of measuring human body dimensions, is used to inform design and ensure that products and environments fit well (Pheasant & Steenbekkers, 2005).

Applying anthropometry is particularly vital and challenging for high-risk, confined environments such as aircraft cockpits, cars, trains, mining equipment, emergency medical facilities, and habitats such as oil rigs, submarines, and off-world accommodations (Harrison & Connors, 1990; Mallam *et al.*, 2015). Designing these extremely confined spaces requires balancing the spatial needs of users with multiple technical systems. Poor sizing and layouts can negatively impact people's ability to work effectively and live comfortably. For instance, a survey of US Navy personnel found that unsatisfactory living conditions, such as cramped cabin areas, berths, and showers, adversely affected performance and crew retention (Wilcove & Schwerin, 2008).

The prototyping tools described here were part of a larger project to enhance habitability on submarines through HCD. The DHMs used in this chapter are based on the Anthropometry Survey for the Royal Australian Navy (ASRAN) data; they employ a boundary manikin approach to identify individuals at the extremes of the target population (Young *et al.*, 2008).

While the collection and analysis of anthropometric data are well-established practices, the tools and methods for effectively applying this data in design processes are less advanced. This gap highlights the need for improved applications to ensure that designs accurately reflect anthropometric insights (Dianet *et al.*, 2018). The relationships between measured body dimensions and the space required by an individual (i.e., environment dimensions) are complex and highly multifactorial. Environments typically need to accommodate various use scenarios, requiring design methods and tools that are efficient and user-friendly so that designers can address all scenarios within project time and budget constraints. A design brief may include requirements, such as "95% of users should perform task X successfully". This is typically assessed by evaluating whether the body sizes at the extremes of the target population can complete the task.

The HCD approach engages users throughout the design process to understand their tasks and environments (International Standards Organization, 2010). Users provide context, use scenarios, and insights into system and environment interactions as well as feedback and evaluation during the design process. Understanding user activities is crucial for interpreting and applying anthropometry effectively.

11.2.2 Prototyping, early and often

Prototyping occurs throughout the design process, transitioning ideas from vagueness to clarity and serving as a shorthand for design (Kelly, 2001). Prototypes give form to abstract concepts and supplement incomplete mental models (Camburn *et al*., 2017). Mock-ups create hands-on experiences, and their unfinished nature helps people understand that they are tools for communication and idea generation (Vaajakallio & Mattelmäki, 2007). The type, detail level, visual characteristics, and functionality of prototypes evolve during the design process.

Early-stage models help designers and clients understand problems and redefine requirements (Andriole, 1994). Simple models open the solution space and suggest more opportunities, making them suitable for early stages. In contrast, detailed models narrow the solution space and are used later (Vaajakallio & Mattelmäki, 2007). Deciding on the appropriate level of abstraction for each design stage and addressing specific issues is part of the designer's craft (Säde, 2001).

Using accurately posed DHMs in the early stages of CAD modelling and as drawing underlays is crucial for understanding how the design should be configured to accommodate various body sizes. Early integration of anthropometric data helps avoid many problems later in the design process (Demirel, *et al*., 2022; Högberg, 2005; Meister & Enderwick, 2001) and reduce time and cost (Zhang & Chaffin, 2005).

11.2.3 Existing tools and methods for applying anthropometry

There are two main prototyping approaches for applying anthropometry as part of the design process: simulation with digital modelling and physical model making.

Table 11.1 shows digital and physical prototyping techniques used throughout the design process for the application of anthropometry, based on the design double diamond format (Design Council, 2018). The design double diamond process, developed by the Design Council UK in 2005, provides a visual representation of a structured, iterative approach to design that promotes divergent and convergent thinking through four distinct phases: discover, define, develop, and deliver. It encourages designers to explore a wide range of ideas before narrowing them down to the best solution, ensuring a thorough and user-centred approach to problem-solving.

In general, existing tools for applying anthropometry are challenging to deploy, making it difficult to integrate them early and often in the design process (Perez Luque *et al*., 2022). When using DHM software, designers must manually manipulate body positions on the screen.

Achieving accurate and realistic poses in a timely manner can be challenging, creating a significant barrier to the frequent use of these tools. This is particularly problematic during the early stages of design when concepts are rapidly evolving, and prototyping needs to be efficient and straightforward. The time and effort required to position DHMs accurately can deter designers from incorporating them into their workflow, potentially leading to less user-centred designs that do not fully consider the physical experiences of different body sizes. Streamlining this process is essential to encourage the consistent use of DHMs throughout the design process, ensuring better ergonomic outcomes and more inclusive product solutions. The DHM posing system described in this chapter was developed to address this problem.

Table 11.1. Methods for applying anthropometry as part of the HCD process for isolated confined environments.

Stage	Activity	Prototyping with DHMs	Physical prototyping
Discover	The problem exploration stage gathers information about users, their needs, and the context. It defines the population and determines the range of sizes to be addressed.	Anthropometric data is analysed, and DHMs are developed to fit the chosen population. CAD and VR models explore and establish technical and ergonomic constraints, with neutrally posed DHMs included as scale references.	Simple physical models are made that capture the sizing of the environment and major components. These models help the design team visualize and understand the problem, and engage users to describe their needs and issues.
Define	Findings from the Discovery stage are used to define size, reach envelopes, and tasks constraints. User needs are described as scenarios and criteria, guiding the interpretation and application of anthropometry and DHM poses.	Anthropometry data is interpreted to define spatial constraints in the environment. DHMs are posed according to use scenarios identified in the Discovery stage.	Physical prototypes that define key dimensions for human fit are created to support activities in the Develop stage. These prototypes enable designers to test and refine ergonomic aspects through hands-on evaluation and adjustments.
Develop	Designs are developed as physical, CAD, and VR models and evaluated by users in an iterative design process. Users are consulted, and DHMs are utilized to ensure the design accommodates the full range of sizes within the population.	CAD models of increasing fidelity are created as part of an iterative development process, built around the DHMs posed in the previous Define stage. This ensures human sizing is considered throughout the Develop stage. VR experiences are also developed, incorporating various sized DHMs, allowing designers to experience spaces in context with different body sizes.	Physical models of increasing fidelity are created as part of an iterative development process. Stakeholders and individuals representing the population's size extremes interact with the prototypes to provide feedback on sizing.
Define	The design is described by explaining how it meets user needs and is sized to suit the required range of people in the user population.	CAD models are created to define the spatial arrangement of the design. DHMs are included to illustrate how the design accommodates various body sizes. The documentation includes VR experiences, flythroughs, static images, and reports.	High-fidelity physical mock-ups are created for stakeholder engagement and final validation activities.

Digital prototyping

DHMs are software representations of humans used to visualize body interactions with a design. Specialist DHM software such as Jack™, Ramsis™, and Safework™ are typically used alongside CAD programs. CAD models are imported into ergonomics software where DHMs are used to evaluate the designs. Alternatively, stand-alone DHMs can be placed into CAD environments for design development and analysis. Crowded spaces like control rooms and public transport can be populated with multiple DHMs.

DHMs can be scaled to reflect the anthropometry of a given user. Scaling is most often done by manually entering a few main body dimensions, for example, stature, weight, and waist circumference, and using (univariate or multivariate) linear regression to estimate other dimensions. The number of dimensions that can be user-defined, and the correlations between dimensions, vary depending on which software is used.

Digital assessments using DHMs are cost-effective compared to physical models and can be used earlier in the design process (Demirel *et al*., 2022). They allow simulation of any population size. However, operating DHM software is mostly manual and difficult to use (Demirel *et al*., 2022), including posing DHMs and generating motion. Motion simulation is complex; thus, DHM software currently offers only basic automated posing tools. Often, inverse kinematics is used to aid posing, i.e., the user can place an end-effector (usually the fingertip or foot), and the corresponding limb position will be determined by the inverse kinematics. This moderately speeds up the posing process; however, posing a DHM in a scene is still time-consuming and requires expertise.

Physical prototyping

Designers use physical prototyping techniques to ensure a good fit between the environment and the range of body sizes in the target user population. Although more time and resource consuming than digital models, physical prototypes provide the most direct experience of the environment. They provide the experience of factors that digital assessments do not, such as touch, sound, and lighting. Physical prototypes also enable finer and more realistic problem detection, like collisions and awkward postures (Chaffin, 2009; Duffy, 2012) and allow non-expert users to navigate and experience the space freely. The confidence level for design assessment through physical prototypes is higher than with digital models (Dianat *et al*., 2018).

The full-sized DHM cutouts in Figure 11.1 illustrate the extreme body sizes required for a project. Note that the tallest and shortest designers in the team (shown on the left) do not represent the population extremes. Evaluating a physical prototype using designers' own bodies is problematic; care must be taken to ensure their personal experiences are not used as substitutes for users of all sizes. For example, a designer developing a kitchen will experience bench height, sight lines, and storage access based on their own body size. Consulting anthropometric data, using DHMs in virtual models, and observing and interviewing users of extreme body sizes can help. However, the designer lacks direct experience with other body sizes and must remember that their physical experience should not be solely relied upon for decision-making.

Figure 11.1. 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 solution is to involve individuals who closely match the extreme body sizes needed for the design; for example, the people on the right in Figure 11.1 were chosen for this reason. However, recruiting enough individuals of extreme body sizes for statistically significant results can be challenging.

People come in various body sizes, shapes, and proportions. For instance, individuals of the same height can have different leg-to-torso ratios. Thus, selecting individuals representing population extremes requires careful consideration and compromise. Typically, people are chosen based on height and weight, but for tasks like seated activities, leg-to-torso proportions may also be crucial. This adds complexity to using people for evaluating physical prototypes.

11.3 Developing new tools and methods – real anthropometry experience system

11.3.1 Background and considerations

The real anthropometry experience system (RAES) is SCHED's solution to address the limitations of current DHM tools. The tool was developed with the following considerations in mind.

1. The maturing of gaming software (the Unity™ engine), motion tracking (Kinect™), and VR technology (Oculus™ headsets) provide an accessible and cost-effective platform to (a) develop immersive environments, (b) enable VR experiences, and (c) track people's body movements in real time and match these to DHMs.
2. Posing DHMs 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 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) a DHM pose capture tool, and (b) an immersive VR experience.

11.3.2 DHM Pose Capture Tool

To use the DHM pose capture tool within the RAES, a designer moves in front of a motion capture device while viewing a screen that shows their movements controlling a DHM in real time within a virtual environment (Figure 11.2). They can switch between different DHMs to experience postures required by various body sizes for the same task (Figure 11.3). The DHM poses can be captured and exported to CAD software for virtual prototyping, making it faster and easier than existing DHM posing systems. This ease of use encourages earlier adoption of DHM in the design process.

The images shown here feature one of the tallest designers on the team. This illustrates the difference in their pose when positioning the small female DHM. Experiencing the extreme contrast between their own size and that of someone with a very different body size gives them greater insight into these differences.

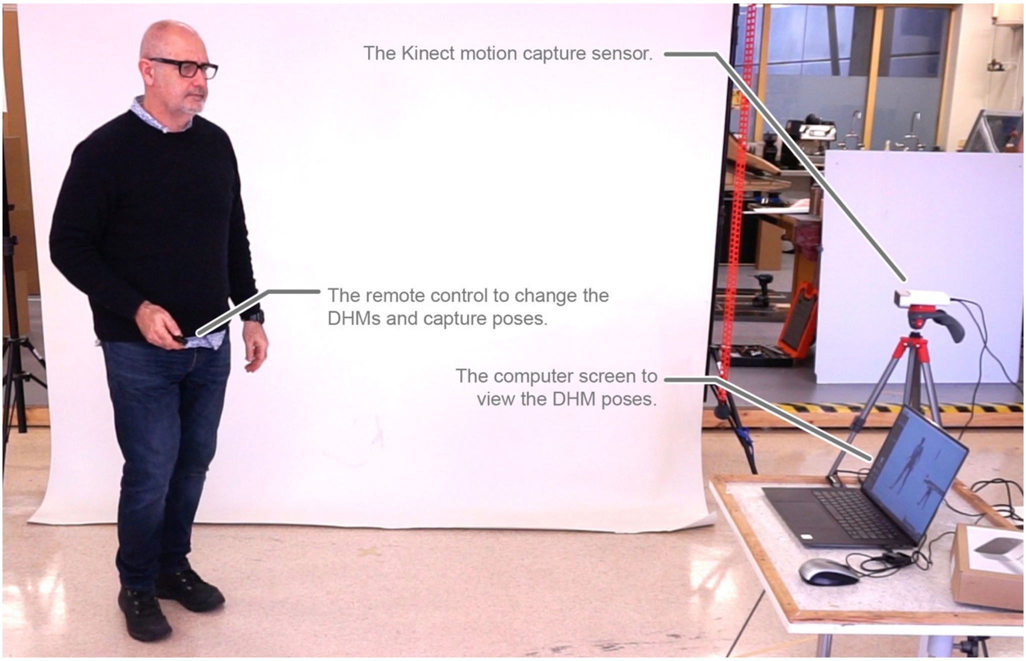


Figure 11.2.
The RAES poser hardware set up: a laptop, a remote control, and a motion capture sensor – in this case, a Microsoft Kinect™.

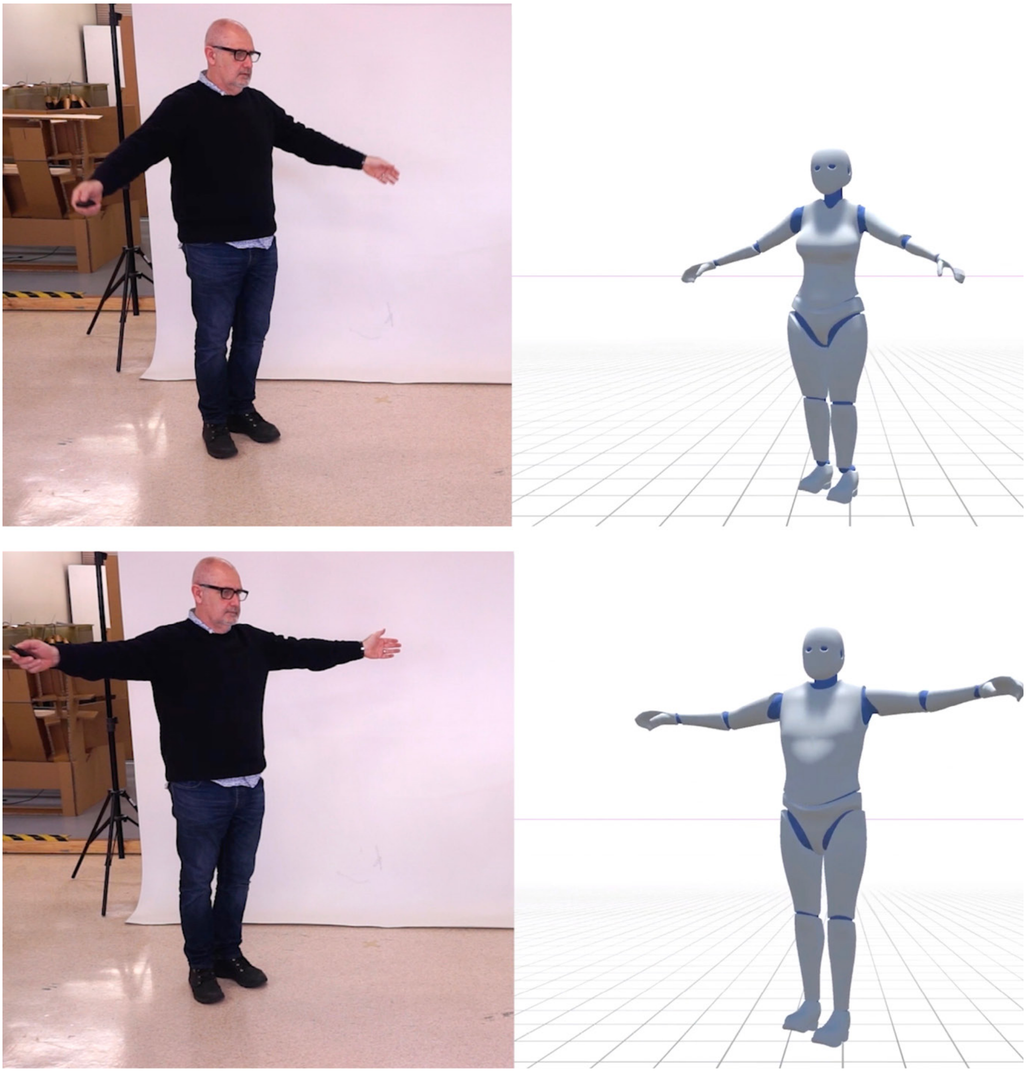


Figure 11.3.
A designer's pose being reproduced by a small female DHM (top row) and a large male DHM (bottom row).

A key feature of the RAES is the ability to import a CAD model, allowing DHMs to be posed in context. Figure 11.4 shows DHMs posed to reach a high, wall-mounted handle. The designers have different experiences when evaluating a physical model due to their varying body sizes. However, when using RAES, their body pose changes to simulate the posture of a person with a different size. Note how similar the poses are for the designers when simulating different DHM sizes.

This ability to experience different body sizes in context is a key feature. People of any body size can experience a range of different body sizes, via direct physical sensations that would otherwise be impossible to experience. For example, a large designer can experience the space and perform tasks as if they were a smaller size. Similarly, a smaller team member can gain insights into the postures and physical movements of a larger person. The key outcome for design discovery methods is to create a deeper understanding of people and thereby challenge the inherent biases of designers. This ability to pose as different body sizes provides a unique way to challenge the body size bias of the designer.

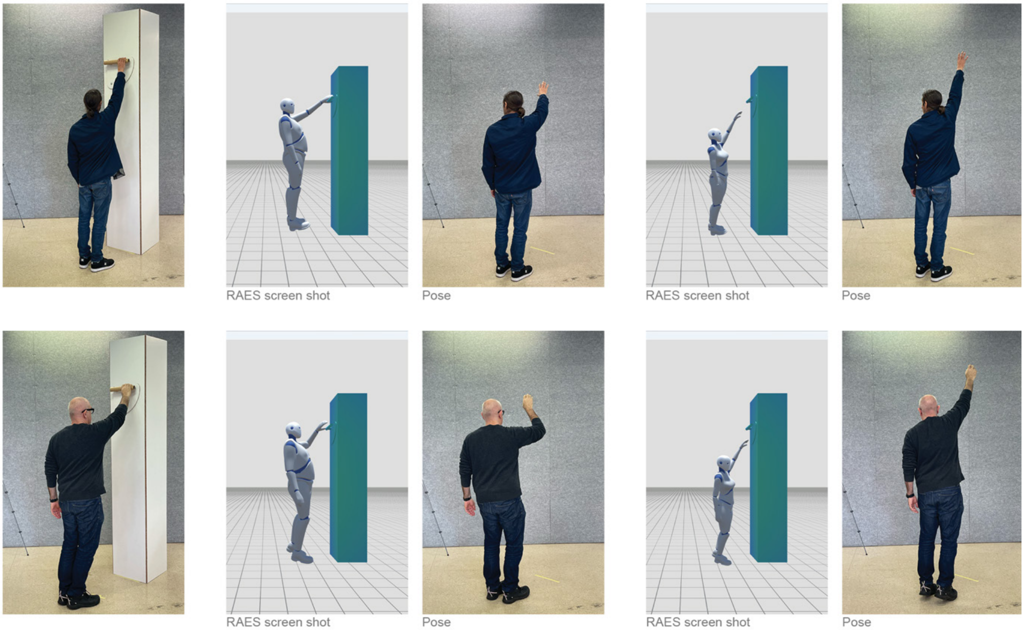
Figure 11.4. The postures of the designers of different heights when using RAES to reach the same target.

Evaluating handle reach on a physical model.

Evaluating handle reach using the RAES.

Large male reach evaluation.

Small female reach evaluation.



Users with different heights will have different experiences when evaluating a physical model.

Although users vary in height, their postures for both the small DHM and the large DHM are very similar.

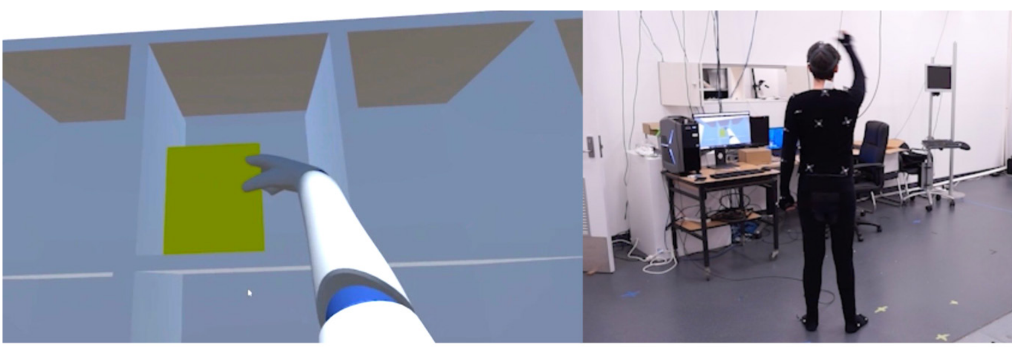
11.3.3 The immersive virtual reality experience

The designer enters a virtual environment, inhabiting a DHM that moves in real time with them. They can select various body sizes to evaluate the reach and sightlines of people with different statures and body proportions. This provides a direct physical sensation and experience otherwise impossible to achieve. Real human movement through the virtual space eliminates the need for digital motion simulation.

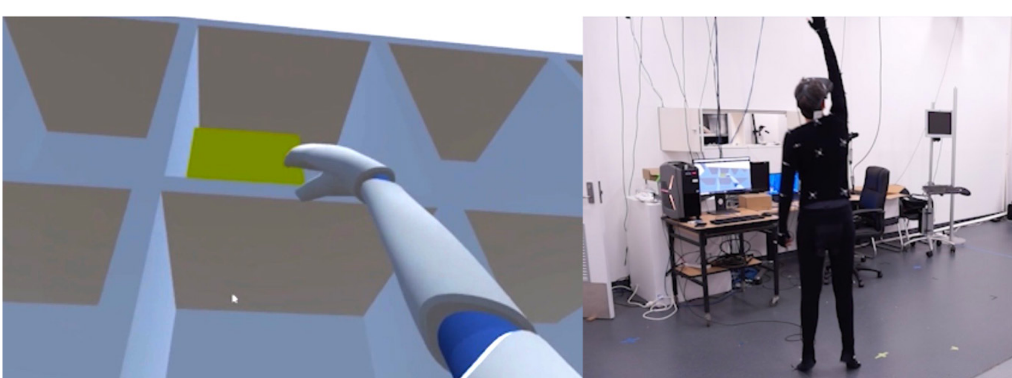
The system requires a VR headset, computer, and body motion tracking. The current tool uses the Optitrak™ motion capture system, which needs passive reflective markers on the body and an expert setup. This setup is cumbersome and contradicts the goal of user-friendly integration: advances in marker-less motion capture are expected to resolve this issue soon.

Figure 11.5 shows the VR tool in use in the RAES, with the user inhabiting a large male (top row) and a small female (bottom row), simulating reaching a yellow box on a high shelf. The images on the left display the VR headset's point of view. Note the different postures: the large male takes a lower, easier posture, while the small female stretches more to access the box. Additionally, the small female has a restricted view of the box compared to the large male. In the images

Figure 11.5.
The postures taken by a designer when inhabiting different body sizes to see an object on a shelf.



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.

shown here, a shorter team member is demonstrating a virtual reality experience. This highlights how different their pose is when positioning a large male DHM.

11.4 The tools in the context of HCD and Empathy

The previous section described the tools developed for manipulating DHMs to aid the design process. The RAES and approach to applying anthropometry in design can be understood within four concepts for prototyping:

1. Methods to develop empathy for users.
2. Physical implicit experiences.
3. The use of mixed methods for applying anthropometry for design.
4. Tools to simplify the integration of DHMs in the early design stages.

Of particular importance are the physical movements used to pose the DHMs. Existing DHM software adds a layer of abstraction to the posing process, requiring designers to manipulate DHMs using computer interfaces and view them on a screen. This removes the designer from the physical experience of the poses, transforming the 3D experience into a 2D screen-based interaction. Such abstraction creates barriers, not only in the transparency of the interface but also in the designer's experience. They lose the implicit, personal understanding of the poses and, consequently, the sense of what these poses feel like.

Designers must understand how people with different body sizes physically interact with their environment. Empathy is the ability to view the world from another person's perspective – to see what they see, feel what they feel, and experience things as they do. This is essential in HCD as it allows designers to understand users' needs, experiences, and challenges. Designers achieve this empathic state by setting aside preconceived notions and making a conscious effort to understand the ideas, thoughts and needs of others (Dam & Teo, 2024).

By fostering empathy, designers can create solutions that are user-centric, addressing real problems and enhancing usability (McDonagh & Thomas, 2010). It shifts the design framing to an understanding that "others aren't the same as me" and challenges our own biases (Krznaric, 2015). One way to describe this is the concept of a person's empathic horizon, "… the boundaries of experience, knowledge and understanding in relation to other people…" (Thomas *et al*., 2012, p. 293). This is developed unintentionally but can be stretched by experiences.

Empathic modelling (i.e., experiencing with your own body the physical situations of others) is a strategy that helps to stretch a person's empathic horizon (Thomas & McDonagh, 2013). It is the physicality of the experience that is key to fostering a deep and rich understanding. While learning via observation is effective, it is rarely as effective as physical practice (Larssen *et al*., 2021). When designers physically engage with the environments and tasks their users will encounter, they gain firsthand insight into the challenges and nuances that might not be apparent through digital models or theoretical analysis.

No single tool or method will provide all the information required to develop a successful design, and HCD practice is typically conducted with mixed methods (Savolainen & Hyysalo, 2020). This tool is intended to be used in parallel with a range of quantitative and qualitative methods, each with its strengths that make up for the weaknesses of the others. For example, physical model making allows for actual physical interaction with the environment, enabling haptic feedback and responses. However, designers cannot directly experience these environments as individuals with other body sizes, and recruiting people that match the extreme body sizes for the specified population poses challenges. On the other hand, using ergonomic software enables the inclusion of a wide range of accurate and detailed body sizes directly drawn from the data. This provides greater confidence that the design is being evaluated against accurate anthropometric data. However, it does not offer a physical understanding of the experience of different poses, and it can be difficult to capture all possible poses and the nuances of actual postures, garment restrictions, and the compression of soft tissue and soft furnishings. The tool demonstrated here offers a unique way of applying and experiencing the data. However, there remains a need to use multiple combined methods to triangulate and ensure confidence in the final decisions (Savolainen & Hyysalo, 2020).

11.5 Conclusion

Designing for human fit in complex, confined environments requires a range of prototyping tools and methods. Existing tools offer a limited understanding of spatial experience and are difficult to use. Based on extensive experience applying anthropometric data in design, new tools have been developed to provide an experiential and empathic experience for designers that existing methods lack. The key element is using designers' bodies to manipulate DHMs, making the process easier, faster, and creating more realistic poses. This gives designers a physical experience of movements as different body sizes, making RAES an advanced form of bodystorming. In addition, easier DHM manipulation encourages use in early design stages.

The ability to use their bodies to manipulate DHMs goes beyond simply making it easier to pose them quickly and easily. The physical act of using their bodies and comparing this motion when posing different DHMs in the same environment and tasks provides a way to gain a physical empathy that other DHM manipulation tools lack. For example, when analysing a reach task, posing and viewing a DHM may identify excessive body extension that could cause discomfort or injury. However, physically experiencing the pose, body extension, and sensations means the designer not only understands but also feels what different body sizes experience. This grants them access to a deeper level of understanding and empathy.

The approach uses DHMs not as quantitative assessment tools but as qualitative aids to help designers and engineers better understand potential design issues. A major challenge with DHMs is their integration into the overall design process, as most tools are part of specialized software packages, adding complexity (e.g., obtaining, installing, and learning software, importing and exporting CAD models). RAES aims to better integrate DHM tools into the design workflow.

Acknowledgement

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12. Urban vision: AI-driven spatial analytics for walkability in Barcelona's superblocks

Aldo Sollazzo

12.1 Walkability indicators

To analyse pedestrian occupancy, several indicators have been introduced to develop an effective data-driven approach to describe infrastructure accessibility (Li *et al*., 2021; Shaaban, 2019), safety (Asadi-Shekari *et al*., 2015) and estimate the actual foot traffic density (Nikiforiadis *et al*., 2020). By doing so, it is possible to estimate the efficiency of pedestrian pathways, identify areas of congestion or underutilization, and ensure that public spaces encourage pedestrian movement.

In urban planning, walkability indicators hold a pivotal role in enhancing the pedestrian experience in urban areas. Several researchers have focused on walkability indicators, considering them "a pivotal method to evaluate the role of the built environment in people's decisions regarding active mobility, supporting the application of public measures that contribute to more sustainable and resilient regions" (Jardim *et al*., 2023, para. 1). To comprehensively grasp this crucial aspect, a multitude of methodologies are used.

12.1.1 Assessing walkability

Forsyth and Southworth (2008) describe a walkable environment from the perspective of urban design. In his exploration, he suggests five additional categories of walkable environments in addition to the conventional walkable environment associated with promoting physical activity:

- *Close*: This refers to a walkable environment that offers proximity to destinations, particularly when driving is inconvenient or unavailable. This perspective aligns closely with transportation planning and often revolves around an individual's cost-benefit assessment.
- *Barrier-free*: A walkable environment categorized as barrier-free implies that it is easily navigable without significant obstacles. Walkability can be fine-tuned to accommodate the needs of children, the elderly, and disabled individuals.
- *Safe*: A walkable environment is deemed safe when it addresses concerns related to perceived crime and traffic safety.
- *Abundant in pedestrian infrastructure and destinations*: A walkable environment conspicuously features comprehensive pedestrian infrastructure such as sidewalks, dedicated trails, marked pedestrian crossings, street amenities, and greenery.
- *Upscale, leafy, or cosmopolitan*: This category describes a walkable place where the pedestrian environment offers a pleasant experience, primarily catering to upper-middle-class professionals with alternative transportation options.

Other studies define computational methods to define and calculate walkability using open data. In their research, Deng *et al.* (2020) introduce a method that includes scraping publicly available datasets, determining varying weights of variables, and generating a synthetic walkability index. The solution introduced contains three steps:

- *Web scraping*: This initial step revolves around extracting open-source data through web scraping, followed by the computation of pertinent variables associated with walkability.
- *Principal component analysis (PCA)*: The subsequent phase involves applying principal component analysis (PCA) to all variables. PCA is used to discern the individual contributions of each variable and assign weights based on the calculated variance.

- *Walkability index*: The final step in this process entails creating a walkability index for each specific location. This index is crafted by amalgamating the determined weights and the contributions of the variables, thereby providing a synthesized measure of walkability.

Walkability can be assessed using computer vision by extracting relevant features from images. Several studies adopt computer vision to assess walkability, focusing on perceived walkability, a deep learning model that predicts the score of perceived walkability using street view images.

Some studies delved into microscale walkability features using computer vision, promoting a deep learning approach that can be used to detect microscale streetscape features related to pedestrian activity, such as sidewalks, crosswalks, and street furniture. For example, Adams *et al.*'s (2022) study demonstrates that "the use of computer vision to detect intersection and street segment features that are conceptually related to pedestrian physical activity (i.e., zebra and line crosswalks, curb ramps, walk signals, sidewalks, sidewalk buffers, bike symbols, and streetlights) is feasible with high correspondence to human raters" (Discussion section, para. 1). The study was conducted using Google Street View pictures (GSV) to train and validate the data, and an open-source platform was implemented to label all data (Wada *et al.*, 2021).

Other approaches adopt street-level imagery as an effective data source for auditing walkable streets, predicting pedestrian volumes and neighbourhood walkability. Specifically, Dorione *et al.* (2022) describe a protocol to obtain two important results. "First, to examine the associations between urban environment features derived from street-level images and walking-to-work rates from the Canadian Census. Second, compare how GSV-derived features predict walk-to-work rates relative to more widely used walkability measures" (Doiron *et al.*, 2022, para. 3).

Computer vision technology and street view imagery can also be used to detect older pedestrians and assess age-friendly walkability. Predicting walking-to-work, street-level imagery, and deep learning can be used to examine associations between walking commuting and features derived from image segmentation and object detection computer vision methods.

One use case of computer vision for extracting the walkability index is in the research of Zhou *et al.* (2019), which measures visual walkability using Baidu map street view (BMSV) in Shenzhen. Their research asserts that "there is no standard approach to assessing walkability. From a scale standpoint, walkability is measured at three levels: the community (point) level, the neighbourhood (area) level, and the street/segment (line) level" (para. 7). The first point and area level are usually described by convenience to daily amenities within an area. Instead of defining the street/segment level, Zhou *et al.* propose a different approach to go beyond "participatory techniques such as field reviews and questionnaires" (Taleai & Amiri, 2017, p. 38), often adopted to evaluate the walkability at this specific scale. The core of Zhou *et al.* (2019) is to describe alternative metrics, adopting computer vision to describe walkability indexes. They explain the usage of four specific values extrapolated from the segmentation of GSV images to determine psychological greenery, visual crowdedness, outdoor enclosure, and visual pavement. Lastly, they introduce the concept of integrated visual walkability (IVW), which is determined by aggregating the previous four subclasses and expressed in a domain range of 20 to 100 (Table 12.1).

In order to segment the images, the authors used SegNet, a type of deep convolutional neural network (CNN) architecture designed for semantic image segmentation, which enables the classification of each pixel of an image into a predefined category. It is considered the best choice due to "higher segmentation accuracy than the K-Means and SVM [Support Vector Machine] algorithms", and the comparison among the different solutions indicates that "deep learning techniques are stronger in processing street view imagery" (Zhou *et al.*, 2019, Segmentation Accuracy and Validation of IVW section, para. 1). Furthermore, the researchers contrasted the walkability results with subjective scores, showing the potential of their approach to entangle the individual perception of the urban environment. The authors conclude that "innovative contributions have been achieved in two aspects: (1) a newly integrated IVW has been developed, and (2) social inequalities associated with visual walkability are quantified" and that these findings "can inform environmental justice conceptualization and can offer practical insights for healthy city planning" (Zhou *et al.*, 2019, Conclusions section, para. 1).

Indicators	Definition	Formula and explanation
Psychological Greenery	Extent to which the visibility of street vegetation can influence pedestrian psychological feelings	$$Gi = \frac{\sum_6^1 Tn}{6 * Sum}$$ ***Tn***: number of tree pixels; ***Sum***: total pixel number
Visual Crowdedness	Extent to which the visibility of obstacles can influence pedestrian experiences	$$Ci = \frac{\sum_6^1 Cn}{6 * Sum}$$ ***Cn***: number of obstacle pixels; ***Sum***: total pixel number
Outdoor Enclosure	How the room-like outdoor space is (the ratio of vertical objects to horizontal features)	$$Si = \frac{\sum_1^6 Bn + \sum_1^6 Tn}{\sum_1^6 Pn + \sum_1^6 Rn + \sum_1^6 Fn}$$ ***Bn*** is the number of building pixels; ***Tn*** is the number of tree pixels; ***Pn*** refers to the number of pavement pixels; ***Rn*** refers to road pixels; ***Fn*** refers to the number of fence pixels
Visual Pavement	Psychological impacts of the proportion of road and sidewalk on pedestrian experience	$$Di = \frac{\sum_1^6 Pn + \sum_1^6 Fn}{\sum_1^6 Rn}$$ ***Rn***: road pixels; ***Pn*** refers to the number of pavement pixels; ***Fn*** refers to the number of fence pixels
IVW	Integrated Visual Walkability index	$$IVW = 5 * (G - level + C - level + S - level + D - level)$$

Table 12.1. Indicators and their definition, formula and explanation for evaluating integrated visual walkability (IVW), adapted from Zhou *et al.* (2019).

12.1.2 Estimating walkability in Barcelona

Jardim *et al.* (2023) focus on methods to provide a more granular description of occupancy levels, describing a score for every one-metre street point, considering it beneficial for "policymakers and urban planners to support the evaluation of current street conditions and access areas that are underserved, as well as plan and gauge new local interventions, while objectively understanding their impacts on pedestrian mobility" (Conclusion, Limitations and Future Work section, para. 11).

Related to the case of Barcelona, another study delves deeper into the compatibility of walkability indicators with the vision of the 15-minute city (FMC), "a new holistic model for urban planning that gains momentum in the debates revolving around the development of sustainable cities" (Ferrer-Ortiz *et al.*, 2022, p. 146). The FMC concept aims to ensure that essential urban services are accessible within a 15-minute walk or bike ride. In their study, Ferrer-Ortiz *et al.* (2022) adopt walkability concepts to map the accessibility and proximity potential of Barcelona based on pedestrian travel times. Regarding its impact on walkability, the researchers assert that "76% of the analyzed blocks [...] have walking access to more than 20 everyday destinations, within less than 15 min" (pp. 156–157). This finding underscores the exceptionally high walkability prevalent throughout Barcelona.

Puig-Ribera *et al.* (2022) introduce a protocol study that "analysed the impact of Superblock environments on health. In this study, we carried out a natural experiment to inform public health policies and practices on the potential that the Superblock model might have on encouraging citizens' physical activity (PA)" (Background section, para. 5). Their study was conducted from May 2018 to May 2019, adopting the system for observing play and recreation in communities (SOPARC) as a critical tool. SOPARC was instrumental in evaluating the sitting, standing, walking, participation in vigorous activities, and utilization of electric scooters among citizens. The research findings suggest that to optimize the effectiveness of the Superblock model in promoting physical activity, strategies should be implemented with a particular focus on seniors and teenagers. This assessment considered gender, age groups, and variations across different times of the day.

12.1.3 Limitations of walkability indicators

Multiple studies render limitations associated with walkability indicators. According to Suzuki *et al.* (2021), walkability indicators may not fully capture the subjective experiences of pedestrians, as individual perceptions can vary based on factors such as personal preferences, cultural background, and physical abilities. First and foremost, the study's cross-sectional design renders it incapable of uncovering causal connections, leaving researchers in the dark about the disparities among older adults and those with mobility limitations. The exclusive reliance on self-reported data introduces the potential for distortion due to social desirability and recall bias. Furthermore, the absence of objective measurements for assessing the built environment's features casts a shadow of doubt on their accuracy. The study's reliance on a convenience sampling approach further restricts the generalizability of its findings, limiting their applicability primarily to lower socioeconomic communities in a specific locale, making it challenging to extrapolate to different built environments. Moreover, the study does not delve into the particular facets of functional limitations most closely correlated with features of walkable neighbourhoods. Lastly, the study's focus on a singular geographic region impacted by a recent public health environmental crisis raises questions about whether external factors influenced responses. These limitations underscore the imperative need for further research to provide a more comprehensive understanding of the intricate relationship between the built environment and functional limitations in older adults.

12.2 Analysing walkability indicators in the Superblock

This section provides an overview of applying multiple techniques for analysing and evaluating walkability indicators. The solutions presented are based on implementing computer vision and machine learning algorithms applied to point cloud data and image processing.

This methodology represents a novel approach providing a dynamic and comprehensive description of the walkability conditions of a given street and urban environment. It achieves this by integrating static and dynamic data, allowing for a complete understanding of the constantly evolving nature of the surrounding environment. The process can be understood as a form of research through prototyping, where computational and visual tools serve as experimental artefacts used to test, evaluate, and refine the understanding of urban walkability. This aligns with the concept of *experience prototyping* (Buchenau *et al*., 2000), where the emphasis is on the creation of prototypes not merely as representations of final products, but as means to explore and communicate experiential qualities of a system or environment. In this context, the analysis pipelines developed serve as means of simulating, observing, and iteratively improving our comprehension of how pedestrians interact with dynamic conditions.

Furthermore, the use of prototyping here supports the framework described as the anatomy of prototypes, where they are understood as both filters and manifestations that enable designers and researchers to isolate and explore specific aspects of a complex system (Lim *et al*., 2008). By constructing a prototype-based analytical pipeline that merges static and dynamic data through computational tools, the method operates not just as a descriptive model but as a systematic and knowledge-generating apparatus, reinforcing the methodological robustness of the research.

12.2.1 Static walkability: 360 image segmentations

The first step with this methodology was to create an image dataset by collecting 360 pictures along the newly installed Green Axes of the Consell de Cent. The images were registered using a special camera, Insta360 X3, mounted on a stick. They were all automatically stored within a few seconds to ensure a high ratio of overlap between each image frame. All image collection was performed by walking around the centre of the road and the lateral sidewalks to capture road characteristics from multiple observation points. The only post-processing applied to the images was removing the operator holding the camera stick by using JPGrm (an image processing suite), ensuring the cleanest image condition for the appropriate 3-D reconstruction (Figure 12.1).

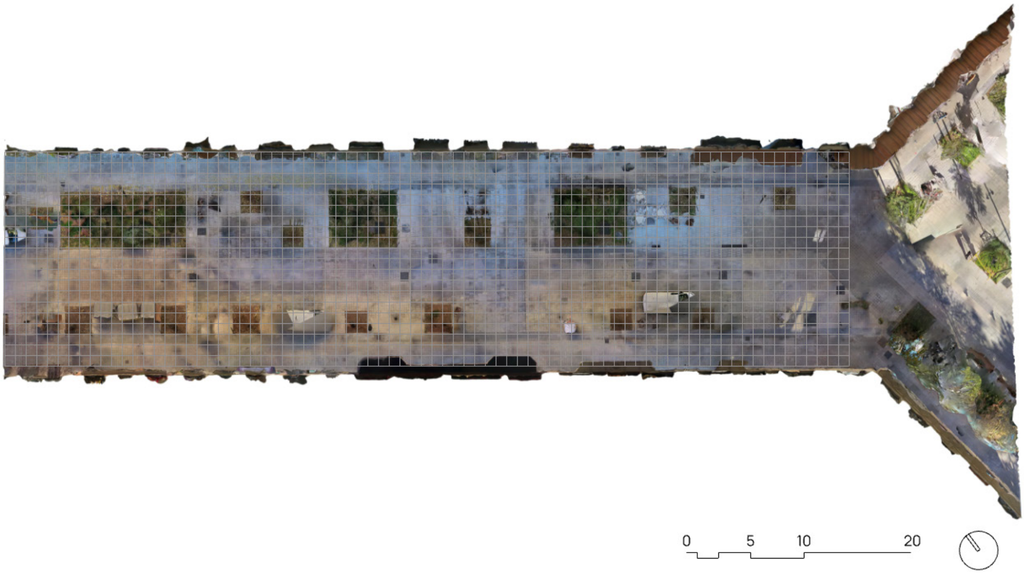

Figure 12.1. Orthomosaic results from the operator removal.

The images were later processed to generate a point cloud using the commercial software of Agisoft Metashape, setting the base for the computational analysis performed on the point cloud (Figure 12.2).

Figure 12.2.
Point Cloud reconstruction of Consell de Cent, Barcelona.

The code segments the images to provide a classification for the principal physical components of the scene. The code is a Python file based on the DEVA library.

The code segments all 360-degree images captured by the Insta 3x camera for two street locations (Carrer de Consell de Cent and Carrer de Valencia) with the DEVA segmentation algorithm. This algorithm generates segmented images by identifying different classes within the images. In this case, the code recognizes buildings, sidewalks, sky, roads, and vegetation. By providing names for these classes, the algorithm generates segmented images that distinctly outline these categories.

From these segmented images, it is possible to extract the area occupied by each class, measured as the total number of pixels corresponding to each segmented region. Additionally, the overall pixel count of the image, determined by the image's height and width, is calculated. These pixel counts are crucial for computing walkability values. The walkability metrics are derived by analysing the proportion of the image area occupied by each class, utilizing predefined formulas to interpret these spatial distributions.

This methodology facilitates the automated training and segmentation process and provides a quantitative basis for evaluating urban walkability through image analysis.

12.2.2 Static walkability: processing

To calculate the formula for integrated visual walkability (IVW) presented in this research, point cloud segmentation was used to measure and quantify the area of each street section associated with every category.

The script starts by importing required libraries such as NumPy, Open3D, Matplotlib, and os. These libraries are essential for handling numerical computations, manipulating point cloud data, visualizations, and operating files.

Following the import statements, two functions are defined: map_level_indicators and downsample. The map_level_indicators function maps level indicators based on predefined thresholds, while the downsample function operates over the point cloud data to reduce computational complexity.

The script then sets file paths for different components of the urban environment, such as buildings, trees, and sidewalks. It reads these point cloud data files using Open3D and applies downsampling to make subsequent analyses feasible without compromising accuracy.

The core of the script lies in calculating various walkability metrics based on the processed point cloud data. Following the research by Zhou *et al.* (2019) described in the previous sections, these metrics include psychological greenery, visual crowdedness, outdoor enclosure, visual pavement, and the IVW index. Each metric offers insight into different aspects of the pedestrian experience, such as the presence of green spaces, crowd density, and walkway accessibility.

Psychological greenery (G_mask) represents the proportion of points classified as trees relative to the total points in the point cloud. This metric indicates the presence and extent of greenery in the urban environment, which can influence pedestrian perception and well-being.

Visual crowdedness (C_mask) measures the openness of spaces by subtracting points representing sidewalks from the total points and dividing them by the total points. This metric reflects the level of congestion or crowdedness in the visual field, providing insights into pedestrian comfort and safety.

Outdoor enclosure (S_mask) evaluates the outdoor enclosure by summing the points representing trees and buildings and dividing by the points representing sidewalks. This metric indicates how outdoor spaces are surrounded by built elements, affecting pedestrian experience and perception of space.

Visual pavement (D_mask) represents a constant value of 1, assuming full coverage of sidewalks or pavement in the urban environment. This metric implies that sidewalks are always present and accessible, contributing positively to walkability.

The IVW index combines the individual metrics (psychological greenery, visual crowdedness, outdoor enclosure, and visual pavement) into a single index. The sum of the metrics is scaled by five to ensure a broader range of values, reflecting the overall walkability of the urban environment.

By calculating these metrics, the script provides a holistic approach to assess walkability, considering various factors such as greenery, openness, enclosure, and pavement quality.

12.2.3 Dynamic walkability: processing

This section presents an alternative approach to dynamically defining the value of visual crowdedness. This computational process can be interpreted as a form of prototyping within design research, where algorithms function as exploratory tools that generate insight through iterative development and testing. Such an approach aligns with the discussion by Celi *et al.* (2023), who argue that prototypes in speculative design research act as epistemic artifacts, tools that materialize hypotheses, enable reflection, and facilitate the generation of knowledge about complex systems. Here, an object detection algorithm has been developed to provide average spatial estimations by recognizing cars, buses, trucks, and pedestrians in a street segment. In this context, the algorithm is not merely a technical tool but also a cognitive instrument, supporting what may be understood as a solution-driven design process, where problem understanding evolves alongside solution development. This corresponds with research on design cognition showing that solution-driven strategies can significantly enhance creative performance, particularly in open-ended design scenarios (Kruger & Cross, 2006). Additionally, the method demonstrates characteristics of information-driven design, in which data is actively gathered and interpreted to shape the design response. As such, the algorithm functions both as a representational prototype and as a dynamic tool for cognitive exploration, reinforcing the methodological depth of the approach.

These classes are detected using the "segment_yolov8.py" script, operating with the YOLOv8 neural network. This model offers high levels of precision, identifying and segmenting moving objects within video frames with a relevant degree of accuracy. Once objects are detected, the areas occupied by these elements are aggregated to compute the visual crowdedness (C), which quantifies the visual density of dynamic entities in the observed environment. The value is recorded for each frame and output as an average within a CSV file format, including time references and urban locations.

The script provides a dynamic analysis of street intersections, adopting state-of-the-art computer vision and machine learning solutions. The algorithm analyses, quantifies, and stores spatial data associated with the presence of a series of objects relevant to the visual crowdedness analysis. The resulting data can be output to the static Walkability indicator to provide a time-based value for a more accurate description of the street conditions. A dynamic analytical approach offers the opportunity to address the public space according to its intrinsic essence, a constantly changing scenario where multiple variables transform its nature, configuration, and usage, and for which decisions and solutions must be introduced according to distinctive moments and cannot be frozen into static solutions.

12.3 Measuring urban indicators

12.3.1 Results from static walkability with 360 images

The results from the static walkability were calculated using 360 images collected at the street level, and a point cloud reconstruction for the two street segments of Carrer de Valencia and Carrer de Consell de Cent, both monitored at the intersection with Carrer de Rocafort.

As shown in Tables 12.2, 12.3, 12.4, and 12.5, the results obtained from the images and the point clouds of the streets were largely uniform across the points of observation. The reason is mostly due to the aggregate results obtained from the analysis and the averaging formulas adopted for the calculation of the results.

The results of visual crowdedness were registered as higher in Carrer de Valencia with Rocafort, indicating a more visually cluttered pedestrian environment. Visual pavement, referring to the quality of the street pavements, was higher in Consell de Cent, suggesting a better-maintained or more visually appealing surface. Additionally, outdoor enclosure, which measures the degree of physical and visual shelter provided by the urban environment, recorded very similar values for both streets.

Table 12.2. Static walkability indicator using 360 images of Carrer del Consell de Cent.

Static Walkability Indicator using 360 images Consell de Cent - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.06	1.42
Visual Crowdedness	0.55	5
Outdoor Enclosure	1.06	4.89
Visual Pavement	6.32	4.72
IVW	–	70

Table 12.3. Static walkability indicator using the point cloud of Carrer del Consell de Cent.

Static Walkability Indicator using the point cloud Consell de Cent - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.05	1
Visual Crowdedness	0.46	5
Outdoor Enclosure	0.87	5
Visual Pavement	1	5
IVW	–	80

Table 12.4. Static walkability indicator using 360 images of Carrer de Valencia.

Static Walkability Indicator using 360 images Valencia - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.07	1.53
Visual Crowdedness	0.57	5
Outdoor Enclosure	1.10	5
Visual Pavement	3.16	4.50
IVW	–	70

Static Walkability Indicator using the point cloud Valencia - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.03	1
Visual Crowdedness	0.75	5
Outdoor Enclosure	1.29	5
Visual Pavement	0.98	5
IVW	–	80

Table 12.5. Static walkability indicator using the point cloud of Carrer de Valencia.

While the static IVW calculation provided some insights, it was not sufficient to fully describe the intrinsic differences between the two street conditions. The uniformity of the IVW values registered did not offer relevant readability to distinguish between the two urban environments. This limitation underscores the need for a more dynamic analysis, which will be presented in the next section.

12.3.2 Results from dynamic walkability indicators

The IVW Index is addressed in this approach as the combination of static and dynamic values. The difference between the existing approaches is the use of computer vision and machine learning to calculate the time-based presence of pedestrians in the urban environment. This integration of temporally sensitive data reflects a prototype-driven process in which computational tools are employed not only for measurement but also for exploration and refinement of theoretical constructs. The visual crowdedness is dynamically computed, integrating it as a variable in the original formula, as visible in Figure 12.3. This use of prototyping supports a research-through-design methodology that aligns with Gaver's (2012) framing of design research as a generative and speculative practice. Rather than seeking to produce definitive, universal theories, Gaver argues that research through design generates provisional and contingent knowledge through the creation of conceptually rich artefacts. In this view, the algorithm and analytical model developed here are not just functional tools but epistemic artefacts – examples of how speculative prototyping can produce conceptually rich insights into complex urban conditions.

Figure 12.3 illustrates the levels of visual crowdedness observed dynamically at the Rocafort intersection with Valencia and Consell de

Cent streets. The crowdedness metric is derived using computer vision and machine learning to analyse pedestrian presence over time. The figure highlights differences in crowdedness between the two intersections (Valencia-Rocafort and Consell-Rocafort), reflecting varying pedestrian activity patterns.

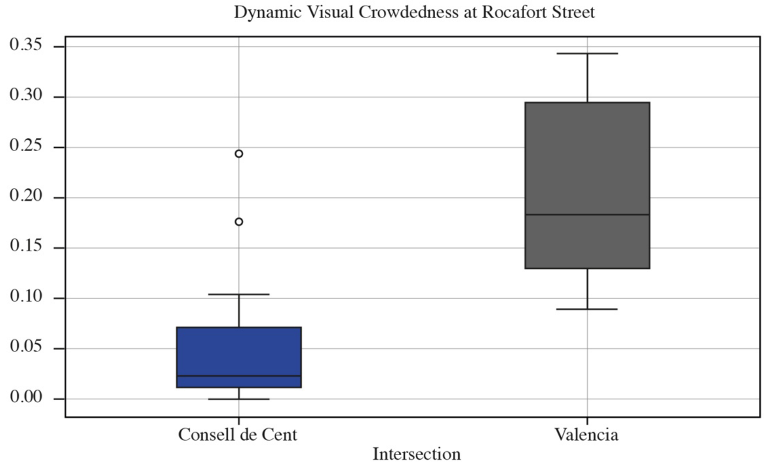

Figure 12.3. Box plot representation of dynamic visual crowdedness at Rocafort with Valencia/Consell streets.

The box plot of Figure 12.3 highlights statistical variability in crowdedness metrics, offering insights into the central tendency, dispersion, and extreme occurrences of pedestrian density. This plot offers the possibility of reading spatial usage and interpreting the interquartile range (IQR). A wide IQR underscores dynamic fluctuations within the

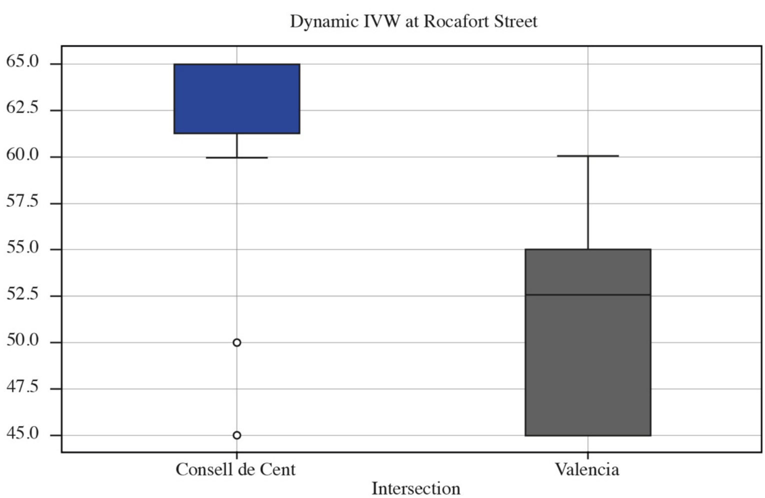

Figure 12.4. Box plot representation of dynamic IVW for Consell-Rocafort & Valencia-Rocafort.

space, while the presence of outliers may indicate localized anomalies or temporally bound phenomena.

The median value registered in Carrer de Consell de Cent is relatively low, indicating that this intersection registers lower traffic. On the contrary, Carrer de Valencia presents a much higher median value and a wider IQR, suggesting bigger fluctuations in street usage.

The incorporation of time-based values into the calculation of the IVW index provides a more comprehensive understanding of the dynamics occurring at the street level. These results underscore the effectiveness of the urban configuration and its ability to attract pedestrian usage, a success attributed to the urban redevelopment initiatives introduced through the Green Axes project.

Constant parameters for Dynamic Walkability Indicator Consell de Cent - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.125	4
Outdoor Enclosure	0.584	5
Visual Pavement	1	5

Table 12.6.
Constant parameters for the dynamic walkability indicator, Carrer de Valencia.

Dynamic Walkability Indicator per hours Consell de Cent - Rocafort			
Time	**Visual Crowdedness**		**IVW**
	Raw	**Level**	
6:00	0.001	1	65
7:00	0.004	1	65
8:00	0.024	1	65
9:00	0.176	4	50
10:00	0.094	2	60
11:00	0.081	2	60
12:00	0.243	5	45
13:00	0.027	1	65
14:00	0.031	1	65
15:00	0.025	1	65
16:00	0.019	1	65
17:00	0.104	2	60
18:00	0.044	1	65
19:00	0.020	1	65
20:00	0.019	1	65
21:00	0.011	1	65
22:00	0.004	1	65
23:00	0.004	1	65

Table 12.7.
Dynamic walkability indicator per hour in Carrer de Valencia.

Tables 12.6 and 12.7 present the calculated values for each intersection. These tables reveal the impact of incorporating time as a parameter in the walkability calculation, enabling a dynamic interpretation of how urban intersections are utilized throughout different periods.

Table 12.8. Constant parameters for the dynamic walkability indicator, Carrer de Valencia.

Constant parameters for Dynamic Walkability Indicator Valencia - Rocafort		
Metric	**Raw**	**Level**
Psychological Greenery	0.186	4
Outdoor Enclosure	1.048	5
Visual Pavement	0.235	5

Table 12.9. Dynamic walkability indicator per hour in Carrer de Valencia.

Dynamic Walkability Indicator per hours Valencia - Rocafort			
Time	**Visual Crowdedness**		**IVW**
	Raw	**Level**	
6:00	0.09	2	60
7:00	0.13	3	55
8:00	0.13	3	55
9:00	0.19	4	50
10:00	0.27	5	45
11:00	0.31	5	45
12:00	0.27	5	45
13:00	0.31	5	45
14:00	0.30	5	45
15:00	0.34	5	45
16:00	0.34	5	45
17:00	0.26	5	45
18:00	0.16	3	55
19:00	0.13	3	55
20:00	0.17	3	55
21:00	0.16	3	55
22:00	0.11	2	60
23:00	0.10	2	60

Tables 12.6, 12.7, 12.8, and 12.9 present a different scenario from the static analysis. The values registered from the dynamic calculation are, in fact, more sensible to the actual usage of the street, considering the presence of pedestrians and dynamic obstacles, offering a contrasting picture of the two locations monitored in this study.

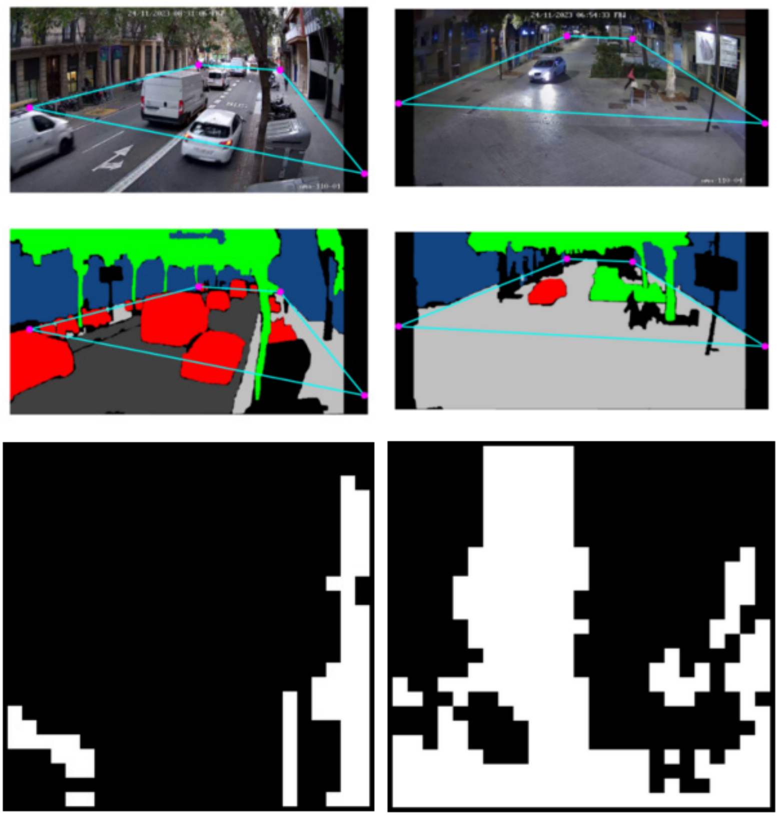

Figure 12.5. Pedestrian masks were transformed in both Valencia (left) and Consell de Cent (right) with Rocafort on 24 November 2023.

The dynamic walkability calculates the accessible pedestrian space by applying multiple masks for specific categories of elements observed in the scene. As pictured in Figure 12.5, a green mask is applied to the vegetation, a red one for vehicles, a blue one for the road, and finally a grey one for the pedestrian road. In the third step of the transformation, a homography matrix is processed to project planarly the space, creating a final map to render in white the walkable area and in black all the inaccessible spaces of the public scene.

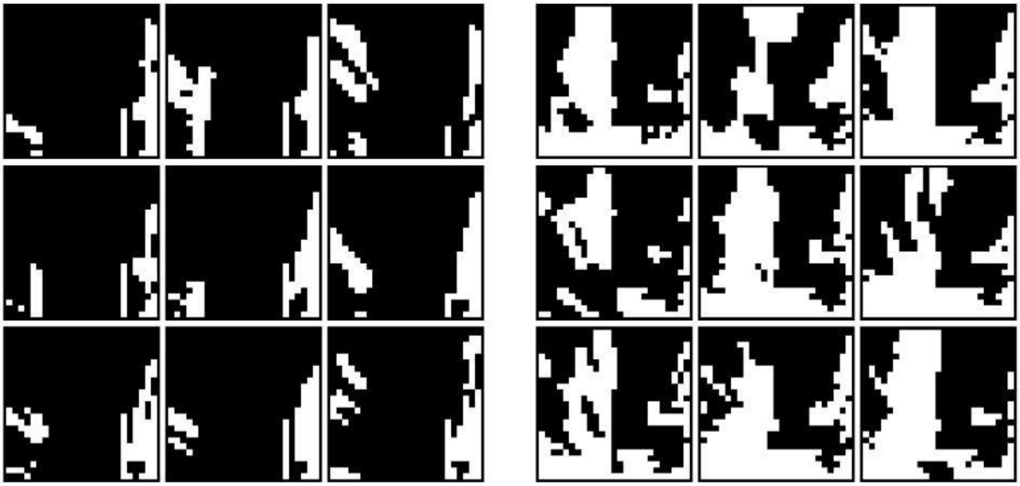

Figure 12.6. Evolution of the pedestrian mask in Carrer de Valencia across one day (left). Evolution of the pedestrian masks in Carrer Consell de Cent across one day (right).

This visualization is organized in multiple frames, describing multiple time conditions, and rendering the dynamically transformable pedestrian accessibility of the shared platform promoted by the Green Axes.

In conclusion, the dynamic walkability assessment emphasizes the importance of real-time data in understanding pedestrian behaviour and preferences. Unlike static assessments, which provide a snapshot based on aggregated data, dynamic assessments offer a more fluid and responsive analysis.

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Contributors

Dr. Ayşe Özge Ağça is is a post-doctoral researcher who researches women's healthcare, focusing on developing tangible tools and employing autoethnographic methods supported by inclusive AR technologies at the ITI/LARSyS, University of Lisbon. Her interdisciplinary work builds on research-through-design approaches and explores how embodied practices can support tangible forms of engagement with health-related data. She holds a PhD from the University of Southern Denmark, where she explored tangible interaction and design anthropology in collaboration with industrialists, design researchers, and students by engaging them with data and everyday objects.

Jack Beven is a software developer and video game designer with a degree in creative arts and digital media. With complimentary skills such as 3D artistic design and front-end web development, Jack is Ekium's primary visualization creator and digital twin developer. Jack is highly proficient in the use of a wide range of visualization technologies such as virtual reality (VR) and mixed reality (MR) headsets.

Yash Bohre is a PhD Scholar jointly enrolled at the Indian Institute of Technology Bombay and Monash University. He holds a major in Mechanical Engineering and a Master's degree in Industrial Design (MDes). With prior experience in user research and healthcare-focused design projects, his current doctoral research explores the development of bespoke and adaptive assistive technologies for individuals with amyotrophic lateral sclerosis (ALS). His work identifies critical gaps between patient needs and existing assistive devices, leading to participatory design interventions integrating hybrid manufacturing, contextual fabrication, and interdisciplinary collaboration. His practice-based research contributes to inclusive design, accessible innovation, and systemic change in care infrastructures.

Rolf Brändle is a PhD candidate at Bauhaus-Universität Weimar investigating how prototyping, model-making, and thinking in mental models advance design research. Using a practice-based approach, he explores how designerly model practices generate knowledge in transdisciplinary sustainability projects and reconcile differing conceptions of "model" through various disciplines. He holds a Thüringer Graduiertenförderung scholarship and was a "Designer in Lab" in the Fraunhofer Network Science, Art & Design. Trained in product design, Rolf lectured and researched at Folkwang University of the Arts (2018–2025) on materials, craft, and sustainability, and worked in the Sustainability by Design project. He is also affiliated with the Forschungskreis at Weissensee School of Art and Design Berlin and the DLab at Bauhaus-Universität Weimar.

Dr. Jacob Buur is a professor of user-centred design at the University of Southern Denmark. He advances the concept of participatory innovation and researches how video and physical objects empower collaboration between stakeholders in innovation projects. Buur directed the strategic research centre SPIRE that brought together researchers from design anthropology, interaction design, interaction analysis, business, innovation management, and a theatre company to collaborate with Danish and international industries. Prior to Buur's appointment at the university in 2000, he established and for 10 years managed the user-centred design group at the manufacturer Danfoss A/S. Here, he designed user interfaces for products like joysticks for excavators and electronic controllers for heating and refrigeration systems.

Tommaso Celli is a biologist with expertise in genetics and microbiology. He is currently a research fellow at the Department of Architecture (DIDA) at the University of Florence, where he is involved in the AERIAL project. His research primarily focuses on biodesign, with an emphasis on the scientific and technological aspects of sustainable, biofabricated, and bioinspired materials. Additionally, he is a member of the spin-off company BIOMA Design LAB, which specializes in biofabricated products and materials.

Francesco Cianfano is a designer and researcher working at the intersection of product design and biodesign in the Material Design for Transition group. A recent graduate with honours in Integrated Product Design from Politecnico di Milano, he is currently continuing his research on Tessitura Calcarea: Bio-induced Mineralization for Material-Driven Design Opportunities, which explores recycled concrete and textile waste as valuable resources through biologically driven processes. His work embraces a materials-driven design approach grounded in ecological thinking, with a focus on circularity and regenerative practices. Through speculative and experimental methodologies, he investigates the potential of biodesign to rethink conventional product design paradigms.

Felicita Devlin is an artist and educator from South Florida, currently living in Providence, RI. They are a studio member of Binch Press / Queer.Archive.Work. Their practice uses craft & technology to express the supernatural dimensions of nature, the mystical presence of disabled, trans, and queer ancestors, and how technology can be used as an extension of survival. Their work relies on experimenting with textiles, printmaking, riso, and digital remixing through coding, 3D design, and sound.

Dr. Rose Dumesny is a designer with a PhD in Design Sciences and Information-Communication Sciences. 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 the 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 to develop methodologies to adapt to it.

Dani Epstein received her Master of Industrial Design at the Rhode Island School of Design and her Bachelor of Fine Arts in Metal from the State University of New York at New Paltz. Her work explores forms, materials, and systems that challenge pre-existing formats, promoting greater sensitivity and flexible futures.

Dr. Silvia D. Ferraris is an associate professor at the Department of Design of the Politecnico di Milano. Her research focuses on methods and tools for the development of new products, from the research to the conceptualization phase, integrating basic design principles and engineering and manufacturing aspects. Silvia has over fifteen years of experience in internationalization processes and in promoting and developing international exchange programs, strategic projects, and networks. Since 2020, she has been the Rector's Delegate for International Relationships of the School of Design, and since 2023, the Rector's Delegate for the Strategic Project "Italy-Azerbaijan University Initiative". The initiative supports ADA University in Azerbaijan in making a new School of Design and Architecture. Since July 2024, she has held a double affiliation between Politecnico di Milano and ADA University, where she is the dean of the School of Design and Architecture. In this capacity, she has developed an expertise in international education, collaboration, and strategic development.

Dr. Francois Fraysse is a senior research fellow at the University of South Australia's Allied Health and Human Performance Unit, specializing in mechanical engineering and biomechanics. His research includes developing biomechanical models for military personnel and assessing physical activity using body-worn monitors. Collaborating with Defence Science and Technology Group and the transport industry, his work has secured over AUD 6M in funding, 44 international publications, and an h-index of 18.

Dr. Purba Joshi is a professor of industrial design at the IDC School of Design, Indian Institute of Technology Bombay. She holds an undergraduate degree in Electronics Engineering, a Master of Design (MDes) and a PhD in Industrial Design, with her research centred on computer-aided design (CAD), creativity, and early-stage ideation in product development. With over two decades of professional design experience and more than 16 years in academia, her work spans healthcare design, assistive technologies, packaging design, and socially relevant design interventions. Prof. Joshi's research and practice focus on addressing complex, real-world challenges through design, particularly creating inclusive and impactful solutions.

Dr. 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. Since 2021 she has guided the work of the Virtual Textiles Research Group (VTRG) based at the Rhode Island School of Design (RISD).

Martina Labarta Labrador is a PhD student in Design and teaching assistant of the Final Project Work course in the MSc in Design & Engineering at Politecnico di Milano. Her research focuses on how product design language can be articulated and employed to challenge existing power imbalances and forms of marginalization by applying a critical and intersectional lens.

Geoff Langridge is a mechanical engineer with experience in a range of mechanical design roles. Problem solving and analysis skills compliment his design and drafting knowledge, offering a broad knowledge base and diverse skills suitable for a broad range of roles and customers. Geoff has a deep understanding of CAD systems and best practices.

Dr. Marco Marseglia is an associate professor at the Department of Architecture (DIDA) of the University of Florence, where he coordinates the Design Laboratory for Sustainability. He is the principal investigator of the project AERIAL and scientific coordinator of the BIODESIGN research unit. His work focuses on product design, sustainability and bio-design with a particular focus on the relationship between design and other sciences. He is currently establishing a spin-off – BIOMA Design LAB – dedicated to biofabricated products and materials.

Dr. Brandon Matthews is an early research career postdoctoral fellow at the Commonwealth Scientific and Industrial Research Organisation. He received his PhD in computer science, specializing in immersive technology in 2023 from the University of South Australia. His research interests include perception and illusions in immersive technologies, human-robot interaction, haptic user interfaces and computer graphics.

Dr. Francesca Mattioli is an assistant professor at Politecnico di Milano. Her research focuses on collaborative practices in design education and how to support intercultural competencies development. She is also studying the potential of project-based learning in design for sustainability education.

Elizabeth Meiklejohn is a textile engineer, designer and researcher specializing in Jacquard and 3D weaving. Her work investigates how novel manufacturing methods and raw materials can inform the performance properties, dimensional qualities and interactive potential of woven textiles. She received an MFA in Textiles and a BFA in Apparel Design from the Rhode Island School of Design.

Simon Modra, an expert in interior architecture, furniture design, building design, and project management, holds a Master of Architecture, Master of Design (Design Construct), and Bachelor of Architectural Studies. A PhD candidate and researcher at the University of South Australia, he co-founded the Studio for Complex Human Environment Design. His research focuses on using simulation tools to optimize design methods for human spaces in capsule environments.

Dr. Nithikul Nimkulrat is a full professor in the Faculty of Design at OCAD University in Canada and was a visiting professor at Politecnico di Milano's Department of Design in Spring 2025. As the recipient of the 2022/2023 OCAD University Award for Distinguished Research, Scholarship and Creative Activity, her research focuses on experiential knowledge utilized, generated, and accumulated in craft and design practice performed as a research method. Nithikul is the convener of DRS Special Interest Group on Experiential Knowledge (EKSIG) (2013–present).

Dr. Rowan Page is an industrial design practitioner and researcher investigating the intersections between theory and practice, between artefacts and systems, and between making and discourse. His award-winning industrial design practice is underpinned by research rigour, collaboration, detail, process, and context. His work demonstrates the role of design in research translation and explores how artefact creation materializes ideologies and fundamental research. He has collaborated with leading Australian manufacturers (Cochlear, Blundstone, and General Motors Holden), hospitals, and fundamental and clinical researchers. He also explores emerging design practices through self-directed practice. He is based at Monash University in Narrm/Melbourne as a Discovery Early Career Researcher Award (DECRA) Fellow (2024–2027) with the Australian Research Council.

Dr. Gemma Potter is a research associate at the School of Art and Design at Manchester Metropolitan University, currently working on the DCMS-funded Stockport Creative Campus project as part of Design Factory Manchester. Her research explores the transformative potential of making through inclusive and participatory approaches. Utilizing creative practice, her research contributes to our theoretical understanding of the relationship between craft practice and gaming. She is currently Co-Editor of *Craft Research*.

Dr. Valentina Rognoli is a designer and researcher working at the intersection of materials design, biodesign, and regenerative futures. She is the leader of the Materials Design for Transition research group at the Politecnico di Milano. Combining critical enquiry with hands-on experimentation, her work promotes a materials-driven design approach informed by ecological thinking and more-than-human perspectives. She teaches and collaborates internationally, developing projects and publishing work on materials design, biodesign, regenerative design, and sustainable innovation in design education. Her other research interests relating to materials include craft practices, indigenous knowledge, and multispecies design approaches.

Dr. Dorian Reunkrilerk works at the ACTE Institute (UR 7539), Panthéon-Sorbonne University, "Design, Arts, Medias" research group. Dorian holds a PhD in Design Sciences and Information-Communication Sciences (specialized in service and graphic design). He worked for four years for museums and design events in curating and cultural mediation. Through his design practice, his research works explore modes of mediation between design cultures within organizations from the point of view of objects and their media properties.

Sisse Schaldemose is an associate professor at the Department of Social Work, VIA University College, Aarhus. She holds an MSc in IT Product Design and a BA in Social Work. Her work is situated at the intersection of design, pedagogy, and social work education, with a particular interest in how material and participatory methods can support reflection, theory learning, and student engagement. She is affiliated with the research programme The Good Life – Pedagogy and Social Innovation under the Social Education Programme at VIA.

Dr. Peter Schumacher holds a Bachelor of Architectural Studies from Adelaide University and a Bachelor of Industrial Design (Honours) from the University of South Australia. His PhD from ANU focused on designing pictorial assembly instructions for developing countries. He has led industry collaborations, including award-winning designs for arthritis-friendly nurse call buttons, and submarine living quarters, utilising user-centred design and anthropometric research methods.

Paula L. Schuster is a PhD candidate and associated researcher at the cluster of excellence "Matters of Activity" at Humboldt University Berlin. Her PhD focuses on the methodology of research through design, exploring prototyping practices in research projects. With a background in communication in social and economic contexts, as well as industrial and interface design, Paula taught and researched as a part of the Interaction Design Lab (IDL) in Potsdam from 2018 to 2022. In the PROTOTYP research project, she investigated prototypes as a communication medium of speculative futures with a focus on participatory prototyping. She has also worked as a freelance consultant for design processes and co-design in the cultural sector.

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.

Aldo Sollazzo is an Italian entrepreneur and technologist who has established himself as a dynamic figure in the fields of robotics, computer vision, and AI. With a career marked by dedication and innovation, Sollazzo's contributions have had a meaningful impact on these dynamic industries. Within the NOUMENA GROUP, Sollazzo's responsibilities encompass leading roles that reflect his commitment to sustainable engineering and architectural innovation. The group is constituted by the three companies of Noumena Data, LAMÁQUINA 3d, and PURE.TECH: the common focus is to establish novel protocols for the definition of built environments informed by data, material technologies, and built through a novel approach of manufacturing.

After an education in experimental physics (MSc 1984), **Pieter Jan Stappers** made the switch to Industrial Design Engineering (IDE) at TU Delft and followed a research path which led from human perception, spatial imagery, Virtual Reality (PhD in 1992), to design tools and participatory design techniques. As a professor of design techniques (as of 2002), he has pursued developing research and education in design techniques for the early phases of design. Core elements in his work are 'research through design', 'experiential prototypes', and participatory techniques such as "contextmapping". On each of these subjects, he has published both in academic books and journals, and developed education materials for broader impact.

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 five 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.

Dr. Dominic Thewlis is a biomechanical engineer and academic at the University of Adelaide where he is Professor and the Head of Discipline for Orthopaedic & Trauma. His award-winning work bridges biomechanics, computational modelling, and clinical decision-making to improve musculoskeletal health. He has held fellowships from National Health and Medical Research Council and the Australian Research Council.

Dr. Jouke Verlinden is Professor at the department of product development and the vice dean at the Faculty of Design Sciences at the University of Antwerp. 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*, and *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.

Yue Xu is a textile designer and HCI researcher-to-be. Their work seeks to extend the materials, tools and agencies of creative technologies. They've been a team member at the Virtual Textiles Research Group at the Rhode Island School of Design and the Textiles Lab at Carnegie Mellon University.

This volume examines the evolving role of prototypes in design research, emphasizing their function as intentional and transient objects that facilitate the transition from abstract concepts to concrete design outcomes. Through a range of disciplinary and methodological perspectives, the book investigates how prototyping contributes to knowledge generation, design process development, and the articulation of experiential understanding. The chapters are organized into four thematic parts – Envisioning, Exploring, Comprehending, and Developing the Design Process – each addressing distinct aims and contexts of prototyping. Contributions include studies on low-fidelity tactics, collaborative learning environments, multisensory material translation, biodesign practices, data engagement, and political dimensions of design. These inquiries foreground prototyping as a situated, relational, and epistemic practice.
The volume concludes that prototyping in design research extends beyond technical validation to encompass pedagogical, ecological, and speculative dimensions. It demonstrates that prototypes can serve as vehicles for interdisciplinary collaboration, critical reflection, and the negotiation of complex design challenges.

FrancoAngeli
La passione per le conoscenze