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The Role of Prototypes in Design Research

Overview and Case Studies

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Chapter 1
Introduction

Silvia D. Ferraris

Abstract In this chapter, we introduce the aim, area, process and methodology, and findings of the research project "PARIDE" (Prototipi Avanzati per la RIcerca di DEsign, Advanced prototypes for design research). The Department of Design of Politecnico di Milano funded the study, which investigated prototypes' role in today's design research. With this study, we intended to get a big picture of this phenomenon highlighting new insights and perspectives for design researchers. When defining the research area, we decided not to focus just on academic findings but also to comprise direct input from the industrial and professional world. As a research methodology, we made the literature review using two parallel approaches: Grounded Theory for a bottom-up analysis and a clustering of collected data for a bottom-down analysis. We developed four theoretical concepts that frame the main phenomena related to the evolution of the role of prototypes and developed a set of essential criteria that describe all prototypes. To show this outcome, we created an interactive visual map. Then we shared our theoretical framework with nine experts who shared their thoughts on our findings and a case study. Through this study, we realized that the meaning of "prototype" has changed over the years because the design is tackling more complex projects—and foremost—more significant issues (i.e., the impact of technology on society, social innovation). Overall, we understood that the multi-faceted landscape of today's design research opens to a wide range of meanings that define what a prototype is and does.

1.1 Aim

The research aims at investigating the role that prototypes play in today's design research. Two prominent and interrelated phenomena define prototypes' role in today's design research. On the one hand, technological evolution enables and requires making new types of prototypes. On the other hand, the evolution of design as an academic discipline continuously widens its perspectives, fields, and research

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methods and—thus—the uses it makes of prototypes (Erlhoff and Marshall 2008; Koskinen et al. 2011; Stappers et al. 2014).

Regarding the first phenomenon, recent technological innovations in advanced manufacturing and virtual technologies allow the making of sophisticated prototypes that can mix physical, digital, and virtual features and support the development and validation of complex products and interactions. Advanced manufacturing technologies accelerate the development process anticipating the possibility of transforming intangible concepts into physical objects (Kamrani and Nasr 2010). Virtual technologies anticipate design features and, for instance, the interaction experience before manufacturing any designed object (i.e., products, spaces, services) (Steele et al. 2002; Stjepanovič et al. 2017; Volino et al. 2015). Likewise, the products designers are called to envision are becoming increasingly complex and often are required to be smart, namely, "digital, connected, responsive and intelligent" (Raff et al. 2020). They are equipped with sensors, processors, and connected devices that support the interaction with digital interfaces, applications, and complex services. Hence, nowadays, prototypes are meant to support a type of design process that relies on the supplementation of new kinds of expertise—such as user experience design, interaction design, and computer science—besides those traditionally integrated (i.e., product design, mechanical and electronic engineering). In this regard, the prototype embodies the translation of different design languages into a developing concept (Hallgrimsson 2012; McElroy 2016; Moultrie 2015).

The second phenomenon is the evolution of design research in the past twenty years. Initially, research about design took place in the industry. It typically pertained to the development of new products for which prototypes played a specific role: representing the last stage of product development before mass production. Indeed, prototypes were made to test, evaluate, and improve the product until the final design and production phase (Erlhoff and Marshall 2008; Geller et al. 2007). When design became an academic discipline—no more than twenty years ago—the scope of its enquiry expanded, embracing new areas of interest (i.e., sustainable design, participatory design, service design, user experience design, etc.) (Barati et al. 2017; Blomkvist 2014; Snyder 2003). This change made prototyping evolve into a theoretical means for doing research. Meanwhile, in academia, design scholars started to investigate the identity of the design discipline and promoted the structuring of relevant methodologies and epistemological approaches. From this perspective, the prototypes' role in design research started to be questioned (Stappers 2007; Yang and Epstein 2005; Wakkary et al. 2015; Zimmerman et al. 2007).

Throughout a one-year research project, PARIDE (Prototipi Avanzati per la RIcerca di DEsign, Advanced prototypes for design research), we investigated if and how these evolutionary pathways define a new role for prototypes in design research. In particular, we enquired into how such sophisticated, integrated, and advanced prototypes support the research in various areas of design, enabling the creation of new products and—furthermost—allowing for the development of theoretical knowledge and the exploration of new research fields.

We aimed to get a big picture of this phenomenon highlighting new insights and perspectives for design researchers.

1.2 Area

When defining the research area, we decided from the beginning not to focus just on academic findings but also to comprise direct input from the industrial and professional world. Indeed, what is developed within companies and professional studios is not broadly shared through scientific publications. Still, we supposed that, on the one hand, a large amount of relevant research is developed in big companies' R&D departments. On the other hand, diverse design professionals are now on the market, offering new and interesting kinds. On the other hand, various design professionals are now on the market offering new and interesting expertise.

Furthermore, we wanted to consider the evolution of the role of prototypes over time. We knew that going a few decades back, we would find prototypes mainly employed in product manufacturing rather than in academic design research, and we did want to recognize that passage. Therefore, in the selection of literature and case studies, we defined that design research comprised both the research made by professional designers for business purposes and the academic research made by researchers for scientific purposes.

Secondly, we framed the research area starting from *product design* and all the design fields (material design, interaction design, etc.) and the other disciplines (i.e., engineering and computer science) that concur with the project of nowadays advanced products (Barati et al. 2017; Gill 2013; Hallgrimsson 2012; Houde and Hill 1997; Moultrie 2015; Niedderer 2013; Pei et al. 2011; Sanders 2013). Then, during the collection and review of the literature about design research, we realized that it was better not to exclude any design field because they are interconnected and share methods and tools. Thus, we included some references from service design (Blomkvist 2014; Kimbell and Bailey 2017), participatory design (Sanders 2013), and critical design research (Forlizzi et al. 2017; Mäkelä 2007; Stappers et al. 2014; Yang and Epstein 2005; Wakkary et al. 2015; Zimmerman et al. 2007), design fiction (Bleecker 2009; Dunne and Raby 2013), aiming to get the most inclusive picture possible.

1.3 Process and Methodology

The one-year research was planned in three main phases, as follows.

(1) Understanding

The first objective of this phase was to map the definitions of "prototype" and to investigate the role it traditionally plays in the design process and its emerging roles in the field of design research. This phase was based on analyzing and synthesizing data from the literature review.

We applied two parallel methodological approaches to the literature: Grounded Theory for a bottom-up analysis and a clustering of collected data for a bottom-down analysis. Through the Grounded Theory (Chun Tie et al. 2019; Noerager Stern 2009; Wolfswinkel et al. 2013), we developed four theoretical concepts that frame the main phenomena related to the evolution of the role of prototypes. While analyzing the literature reviews' data, we developed a set of clusters of essential criteria that describe all prototypes. To show this outcome, we created an interactive visual map highlighting relations between a selection of the most relevant criteria (discipline, aims, and terminology).

The result of the literature review was the definition of an initial theoretical framework describing the role that prototype plays in design research, particularly the aims and ways in which prototypes are used and the types of knowledge they support generating.

(2) Learning from

The main objective of this phase was to validate the theoretical framework. We, therefore, planned a set of interviews with researchers and asked them to share a case study of one of their design research projects where—in their opinion—the role of prototypes was relevant. We selected nine experts from research universities and design consultancies to cover the research area that we were investigating. We shared the literature review and framework outcome with them, focusing the first part of the interview on the four theoretical concepts generated by the Grounded Theory. Then, we collected their examples of prototypes' applications in design research. We based the data collection format on the criteria detected during the literature review. This phase was supposed to be done through direct observation through study tours, but it was mainly done by interviews due to the pandemic situation.

Eventually, the case studies were compared and analysed by making an interactive visual tool that enabled us to highlight relevant relations of the criteria defined during the research.

(3) Describing

The ultimate goal was to describe an overview of the design research phenomenon and the prototypes' related role.

1.4 Findings

In our research, we gained insight into several aspects. First, we realized that the meaning of the term "prototype" had widened because of the phenomena earlier mentioned—i.e., the technological push and the evolution of design as a discipline.

Indeed, conventionally, prototypes are meant to assess the function and performance of a new design before it goes into production; therefore, they represent one of the last steps of the product development process (Erlhoff and Marshall 2008). This standard definition of prototype refers to a concept of design that creates very concrete outcomes (i.e., new industrial products) in a very concrete context (company R&D departments).

Today, the interpretations of the term "prototype" can vary greatly depending on the researcher's background. The term can refer to anything conceived and made to support various design activities (from generating new ideas to exploring new experiences, tackling complex problems, provoking critical discussion, and envisioning possible futures). Some researchers call prototypes any representations of an idea (Fraser and Seaton 2013), regardless of the material and technique employed (from sketches to foam models, material studies, aesthetic models, and scaled mock-ups). While today, design research might be very advanced and yet apply very simple prototypes, not just those sophisticated ones that we expected (Snyder 2003).

We realized that the reason why the meaning of "prototype" has changed over the years could derive from the fact that design is tackling more complex projects (i.e., digital products). But also—and foremost—more significant issues (i.e., the impact of technology on society, climate change, social innovation) that require exploratory and speculative studies (Kymäläinen 2015).

Overall, we understood that the multifaceted landscape of today's design research opens to a wide range of meanings that define what a prototype is and does. On the one hand, we observed that the field of design research lacks a shared definition of the prototype. On the other hand, we understood that the multiple roles that prototypes can play depend on a set of criteria: some regard the research (context, discipline, and general scope), and some regard the features of the very prototype (nature, specific aims, and fidelity). Among these criteria, the most important is the aim. Indeed, in our understanding, research prototypes are defined based on the aim for which they are devised.

Lastly, we used these criteria to develop a framework that gives an overview of the prototypes' roles in design research.

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Chapter 2
Developing a Data Classification Framework

Gabriele Barzilai and Silvia D. Ferraris

Abstract In the first stage of the research project, we reviewed the extant literature on the subject of prototypes in design research, with the aim of developing a data classification framework. The literature review allowed us to investigate both the traditional and the emerging roles that prototypes play in various fields of design research. Data relevant to the study were extracted and interpreted following a top-down approach, based on narrative and critical reviews. The synthesis of the data was then classified according to six criteria: *aims*; *discipline*; *terminology*; *context*; *fidelity*; and *phase of the process*. Such criteria were identified throughout the reviewing process and served as a basis for the development of the classification framework—each criterion became a specific data cluster. Finally, by turning the framework into an interactive tool, we were able to cross-reference the clusters of data in pairs, taking the cluster *aims* as a benchmark. While developing the classification framework, we carried out a second analysis of the summarised literature, implementing the Grounded Theory (GT). This further analysis—performed in parallel with the other—was aimed at gaining a deeper understanding of the subject under examination. As a result of this enquiry, we developed thirteen themes and four theoretical concepts—these concepts interpret the broad phenomena underlying the evolution of the role of prototypes in design research.

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2.1 Literature Review

2.1.1 Selection and Review of Relevant Literature Sources

In the first stage of the research, we carried out a literature review, combining narrative and critical approaches (Paré and Kitsiou 2017). The literature review was driven by two complementary goals:

1. Collecting definitions of "prototype" and similar terms—such as "model" and "demonstrator"—which are well-established and used across various fields of design research.
2. Investigating the role(s) that prototypes play in today's design research.

Because we focused on definitions, our review spanned across different sources, including encyclopaedias, besides scientific journals and books. Moreover, we included books and articles written by practitioners—indeed, design research conducted in or for industry fell within the scope of our enquiry.

In the process of source finding, we relied on keywords, which were selected based on the following categories: *field-specific terminology* (e.g., prototype, mock-up, research artefact, etc.); *relevant disciplinary area* (e.g., interaction design, product design, service design, design research, etc.); and *research area* (e.g., manufacturing techniques, product development, design methodology, service development, etc.). To find and collect the literature sources, we used web search engines and online platforms, such as Google Scholar, ResearchGate, Academia.edu, Mendeley, and Online databases (library of Politecnico di Milano, ACM Digital Library).

Throughout the process of source finding, we selected 95 literature sources among books, journal articles, papers, web articles, and definitions from encyclopaedias—the process lasted four months. For each publication, we collected excerpts of various lengths, which we deemed relevant to our study. Hence, we clustered the excerpts by terminology, disciplinary area, and role of the prototype. After carefully re-examining the clusters, we synthesised the content using a specially designed grid for data analysis, structured into six pre-defined categories:

- **Reference**: literature source.
- **General definition**: short definition of the term "prototype" and similar terms.
- **Extensive definition**: extended definition of the term "prototype" and similar terms.
- **Synthesis**: summary of the publication.
- **Interesting aspects**: content of major relevance for the study.
- **Comment**: researcher's personal notes.

The six categories were defined in accordance with the main goals of the literature review. While synthesising the clusters, some publications were discharged as deemed of little or no relevance. New publications, on the other hand, were added, drawing on the reference lists available in the literature sources prior reviewed. At the end of the process, 63 publications remained, forming the main set of literature sources to be used for the next stages of the analysis (see https://tinyurl.com/e6wrwr57).

2.1.2 Prototypes Beyond Definitions

After synthesising the clusters of excerpts, we extracted over 80 definitions of the term "prototype" and similar terms, such as "model," "artifact," and "demonstrator." By implementing our data grid, we were able to spot inconsistencies and overlaps in the use of the field-specific terminology. In general, we observed that these inconsistencies were due to a twofold linguistic phenomenon, which involves authors and theorists in the various fields of design. The first phenomenon is that different meanings are ascribed to the same term—e.g., the term "prototype" is used to describe both unfinished artefacts that embody the design concept of a product-to-be and detailed artefacts that closely resemble the final product before mass production. The second phenomenon, equal and opposite to the first one, is that the same meaning is described with different terms—e.g., the unfinished artefacts made to embody a particular design concept may be termed "models," "mock-ups," "sketches," "prototypes," or otherwise. Overall, we found that the field-specific literature is riddled with semantic overlaps, which show a lack of a shared understanding among researchers regarding the meaning of the term "prototype" and of similar terms.

Given the lack of uniformity among definitions, we moved our focus to the role that prototypes play in design research, searching for meaningful patterns—see also Ferraris and Barzilai (2021). This way, we sought similarities in the understanding of prototypes, beyond terminology and definitions. Hence, we reorganized our data grid as follows.

- Reference of the publication.
- Role/Aim of the prototype (in the author's interpretation).
- Categorization criteria (aims, discipline, terminology, context, fidelity, phase of process).
- Author's specific distinctions to be highlighted.

In order to grasp the shades of meaning underlying the role of prototypes, we distinguished the general—overarching—aim from the specific—stage-dependent—purposes. This double-layered dimension of the role of prototypes is common to any fields of design research. In the fields of fashion and textile, for instance, samples are made throughout the design process to enable trans-disciplinary communication among all partners involved (Farrer and Finn 2009). These samples can be regarded as prototypes that serve specific purposes, related to distinct stages of the design process. In light of this twofold dimension, in the new data grid, we included the category *author's specific distinctions*. This category allowed us to verify whether and how in each literature source a distinction was made between general aim and specific purposes of prototypes.

Finally, we identified six additional criteria to be used as items of a conceptual structure for a classification framework: *aims*; *discipline*; *terminology*; *context*; *fidelity*; and *phase of the process*. These criteria emerged, as it were, from the first stages of the literature review—we found that some concepts recurred in the description of prototypes given by the authors. The classification criteria were identified by an inductive semantic approach (Braun and Clarke 2006). Below a detailed description of each classification criterion.

Aims Prototypes are commonly defined based on their purpose(s)—what they are made for—rather than on other qualities, such as, e.g., fidelity. Indeed, the essence of prototypes is determined by the purpose they serve and the context of use for which they are designed. This general understanding of prototypes is shared among all authors. To give an example, when a prototype is made to test a user interface in its early stage of development, it may be a very simple "paper prototype", far from the final design. In this case, the low fidelity of the prototype serves the needs of the research, in a particular stage of its process. In brief, prototypes are defined by the purpose(s) they serve in the research process.

Discipline The general role and specific purposes that prototypes play also depend on the researcher's specific disciplinary area. Hence, for each literature source, we identified the specific disciplinary area of reference, deriving this information either from the specific authors' affiliation or from the content.

Terminology We collected all the terms used by the authors to describe the most common design tools. Indeed, given the use of these terms, the boundary between prototypes and other types of design tool is often rather blurred.

Context The approach and the context of the research are key to understanding the role that prototypes play. In this regard, we identified four main approaches and related contexts:

- **Practice**. Professional setting where new products are designed, normally based on unstructured research, which may be carried out either by single designers or by a team working in a design studio.
- **Research-based practice**. Business R&D departments, where innovation is market oriented—the research is aimed at developing new marketable solutions.
- **Practice-aimed research**. Research carried out by academics for external partners (public and private bodies, industrial and service companies). This type of research hinges upon the knowledge transfer from the academic field of design to the professional design practice.
- **Theory-aimed research**. Research conducted by scholars at universities or research centres to advance design-relevant theoretical knowledge. This type of research is carried out independently from clients or external bodies and may not have a direct impact on the design practice.

Fidelity The fidelity describes the extent to which a prototype acts and looks like the finished product (McElroy 2017) and is usually defined by three degrees: low; medium; and high. In product development, as the design process advances, getting closer and closer to the envisaged product, the fidelity of the prototype(s) increases. In our data collection, we distinguished between authors who use the concept of fidelity explicitly, referring to the above-mentioned three degrees, and those whose reference to the concept of fidelity is implicit.

Phase of the process The aim of prototypes is also related to the particular stage of the design process in which they are implemented. We found that prototypes are used mainly in four stages of the design process: (1) conceptualization; (2) design development; (3) product optimisation; (4) testing before production.

2.1.3 Data Cards

The final version of the data grid mirrored our shift of focus, from definitions to contexts and uses of prototypes. At this stage of the process, all 63 literature sources had been synthesised using the conceptual structure of our final data grid. As a way to move from this early stage of data summary to a more structured classification framework, we designed printable cards, based on the data grid. Hence, the data summary of each literature source was printed on an A5 sheet of paper (see Fig. 2.1)—this way, it proved easier for us, and the other researchers involved, to carry out an in-depth analysis of the literature. By accurately scrutinising each data card, we were able to synthesise our entire dataset into an all-comprehensive classification framework. To achieve the synthesis, we followed a three-stage process, described in the next section (Sect. 2.2).

2.1.4 Parallel Analysis

While developing the classification framework, we decided to perform a parallel analysis of the dataset, implementing the Grounded Theory (GT). The aim of this further analysis was to understand more deeply the emerging roles of prototypes in design research. Indeed, the use of an inductive approach allowed us to identify and comprehend the broader social and cultural phenomena underlying today's manifold understanding of prototypes. This approach, moreover, gave us the chance to open the enquiry to unexpected findings. In this regard, we considered the two analyses as complementary to each other—a combination of top-down and bottom-up approaches to the data analysis.

On the practical side, the two complementary analyses were carried out in parallel, every other day—i.e., the two processes were separate. While the classification framework was developed by clustering all the items of the data cards, the grounded-theory

Johnson, B. D. (2011). Science Fiction Prototyping. Designing the Future with Science Fiction. Morgan and Claypool.

Role/Aim of the prototype (as interpreted by the author)

SFPs play the role of means by which to explore "the ramifications of new technologies, develop and test hypotheses, and find solutions to problems that come with pioneering techniques and emerging science." Prototypes are seen as stories that tell about the ultimate result in terms of features of the object/system but also in terms of context and social relationships that such an object/system is inscribed in or/and gives rise to ("Prototypes are not the thing, they are the story or the fiction about the thing that we hope to build") it to explain together what we hope to build.

Categorisation criteria

Aim: "[...] using multiple futures and realities to test the implications and intricacies of theory. Additionally, the output of the science fiction prototype can feed information back into the science and technology development process (more info in Chapter 7), investigating and shaping how a user might encounter, explore and ultimately use that technology" "We then use these fictions to get our minds around what that thing might one day be and we also use".

Discipline: Mainly Engineering (software/hardware engineering, computer science, ubiquitous computing) but also Industrial and interaction design (although it refers more to technology development).

Terminology: Science fiction prototyping (a means to more holistically envision the future development of technology).

Context: Industrial development oriented academic research (he worked at Intel and collaborated with organisations and companies as a futurist; but he is also a prof. at Arizona State University).

Fidelity: There's no reference to the concept of fidelity. Remains, though, the reflection about the fact that "closeness to what it could be like" is a key point of SFPing and therefore fidelity might be implied.

Phase (process): Throughout the process, employing a diversity of means (e.g., comics, short fiction, film). Actually, the framework proposed it is a process itself (structured in 5 steps).

Author's specific distinction(s) (to be highlighted)

SFP framework consisting of 5 steps + specific definition.

Fig. 2.1 An example of the data cards analysis was applied only to a specific part of the dataset (see Fig. 2.8). The process of the grounded-theory analysis is described, step by step, in Sect. 2.3.

2.2 Data Classification Framework

As earlier mentioned, the printable data cards allowed us to advance the analysis from an early stage of data summary to a more structured classification framework. The reason to develop this framework was to endow ourselves with a systematic means to accurately classify the various dimensions that influence the roles of prototypes in design research. More in particular, the aim was to develop a taxonomy of each of the six fundamental dimensions that we identified in the first stage of our analysis—i.e., what in the data cards we labelled “categorisation criteria”. These are (1) *aim*, (2) *discipline*, (3) *terminology*, (4) *context*, (5) *fidelity*, and (6) *stage of the process*. Indeed, once we found that these six dimensions all contribute to determining the role(s) played by prototypes, we understood that we could further investigate our subject by classifying the variety of types falling into each dimension. Hence, each dimension became a cluster, grouping various types. Performed in this way, the classification engendered a broad understanding of the subject matter—we identified both traditional and emerging concepts about prototypes.

As for the development of the classification framework, we followed a three-stage process. First, we parcelled out all the data cards into six parts, each one containing the summary related to one specific dimension or classification criterion (under the label “categorization criteria”, see Fig. 2.1). As a result, we obtained a large set of data (i.e., 378 bits) to be clustered. Second, we sorted these bits of data by specific classification criterion, obtaining six clusters—each one grouping 63 between summaries and single terms. Finally, we mapped the recurring patterns in each cluster, aiming to develop taxonomies. The set of clusters and related taxonomies became the structure of the final classification framework. A detailed description of these taxonomies is given in the next section.

After completing the classification framework, we started working on a data visualisation tool—indeed, the scale and complexity of the classification made it nearly impossible for us to extract meaningful information from the framework. An interactive tool best suited our need to unveil the interrelationships among the six dimensions (i.e., clusters), besides collecting the related taxonomies. Although the very taxonomies were part of the research output, we believed that better understanding the interrelationships among the six dimensions would complement our research with a further contribution of knowledge. To this aim, we developed an interactive tool that allowed us to cross-reference the content of the clusters (i.e., the taxonomies) in pairs, taking the dimension or cluster “aims” as a benchmark. A detailed description of our interactive visualisation tool is given in Sect. 2.2.2.

2.2.1 Clusters and Taxonomies

Following the three-stage process earlier described, we obtained six clusters—one for each dimension—and several taxonomies.

Aim Analysing this cluster, we identified 43 taxa, between types and sub-types. In particular, we found 9 main types and 34 sub-types of aim, as shown in Table 2.1.

Discipline Regarding the disciplinary areas, we identified 15 types, as shown in Table 2.2.

Terminology This cluster contains 66 taxa, between types and sub-types. In particular, we identified five main terms and collected the related sub-types: *artefact* (5 sub-types); *model* (12 sub-types); *object* (6 sub-types), *prototype* (31 sub-types); and *prototyping* (7 sub-types). The terms that were not consistent with these five were

Table 2.1 Types and sub-types of aim

Type of aim	Sub-type of aim
Develop	Simplify (the process) Finalise (the design) Create/design Resolve
Assess	Test Evaluate/analyse Validate Improve
Communicate	Persuade/reassure Show Get feedback Clarify Convey
Comprehend	Understand Share/negotiate Collect (data) Learning
Research	Produce (knowledge) Translate (from abstract to concrete) Identify (problems) Investigate (issues)
Explore	Explore Generate Experiment Experience
Provoke	Instigate Discuss (critical) Speculate
Envision	Foster (imagination/creativity) Anticipate

Table 2.2 Types of disciplinary area

Disciplinary area
Product design
Industrial design
Interaction design
Critical design
Design (art and crafts)
Fashion design
Design fiction
Speculative design
Participatory design
Industrial design engineering
Mechanical engineering
Ubiquitous computing
Service design
Computer engineering
Human–computer interaction

collected in a separate list, labelled "other terms" (19 terms overall). The full list of sub-types is available at the link https://tinyurl.com/3yajc22n.

It is worth to mention that the sub-types are compound words, in which the main term is semantically defined by either an adjective (e.g., *diegetic prototype*) or an attributive noun (e.g., *experience prototype*).

Context This cluster consists of four types, as shown in Table 2.3.

This taxonomy is rather simple, consisting of four types only. However, each one of the literature sources that we analysed refers to more than one type of research context. Indeed, in some instances, the literature source is written by academics, but concerns design practice and targets practitioners. In other instances, the literature source is written by practitioners, but concerns methodology and targets all contexts of design research. Hence, in each literature source, the understanding of prototypes can refer (or be relevant) to two or more research contexts. This complex pattern

Table 2.3 Types of research context

Research context	Description
Practice	Unstructured research, carried out in a professional setting (e.g., design studio)
Research-based practice	Market-oriented research, carried out in business R&D departments
Practice-aimed research	Structured research, carried out by academics for external partners (public and private bodies)
Theory-aimed research	Academic research, conducted by scholars to advance design-relevant theoretical knowledge

Table 2.4 Number of literature sources per research context, sorted by three different lenses

Types of research context	Context of the author(s)	Context of the research presented	Context of the recipient
Practice	1/63	35/63	8/63
Research-based practice	5/63	41/63	21/63
Practice-aimed research	12/63	49/63	56/63
Theory-aimed research	45/63	38/63	56/63

prompted us to use three further categories for the classification of the literature sources, to be cross-referenced to the four types of research context (see Table 2.4). These categories are lenses through which the types of research context referred to in each literature source can be viewed. Each lens focuses on one dimension, as it were, of the literature source: (1) *author's background* (i.e., who writes); (2) *literature content* (i.e., what it is written); (3) *recipient* (i.e., who it is written for). As a result, we were able to analyse the specific types of research context from three different viewpoints: context of the author; context of the research presented; and context of the recipient.

The three lenses allowed us to apply a multi-dimensional criterion to the research context-based classification of the literature sources. Indeed, the research contexts to which the literature sources refer can be identified considering the author, the literature content, or the recipient, alternatively. For instance, as shown in Table 2.4, when we applied the lens *context of the author*, we observed that most of the authors work in the context of academic research (45/63). On the other hand, when the lens *context of the research presented* was applied, we observed that more than half of the literature sources refer to all the four research contexts at the same time. Finally, when we applied the lens *context of the recipient*, we observed that most of the literature sources refer to both the *practice-aimed* and *theory-aimed research* contexts (56/63), while less than half refer to the context of *research-based practice* (21/63), and a few of them refer to the context of *practice* (8/63). It is worth to mention that some overlaps emerge as far as the second and third lens are concerned—indeed, when considering the content and the recipient, some literature sources refer to all the four types of contexts at the same time, although to different extents. The rationale behind this multi-dimensional classification is that the way prototypes are understood in a particular research context can vary depending on the research context of whom writes and theorises about it. For instance, the roles of prototypes in design practice may be understood—and defined—differently, depending on whether who writes and theorises about them is a practitioner or an academic.

Overall, our classification unveiled that researchers write more than practitioners, although they cover aspects of all contexts. Notwithstanding, a few designers working in R&D departments share their findings with a large public (5/63). Finally, based on our observation, the topic of prototypes is almost as relevant to the professional practice (35/63) as it is to academia (38/63).

Fidelity This cluster consists of three types: (1) *low fidelity*; (2) *medium fidelity*; (3) *high fidelity*. The type of fidelity is thus defined by its degree—that is, the extent to which a prototype looks and acts like the envisioned final product. The taxonomy is here based on both the explicit and implicit references to the concept of fidelity. In this regard, we distinguished between those authors who mention the three degrees of fidelity and those whose reference to the concept of fidelity can be inferred from what they write. Contrary to what we expected, there seems to be little consensus about the understanding of the concept of fidelity among design researchers. Indeed, this concept is well defined only in a few of the literature sources that we analysed.

Stage (design process) In this cluster, we identified four types, which match the four stages of the design process earlier identified in the data cards: (1) conceptualization; (2) design development; (3) product optimisation; (4) testing before production. It is worth to highlight that only few authors made explicit mention to the role of prototypes with respect to the stages of the design process. Thus, it is hard to assess the significance that this relationship has for the understanding of the roles of prototypes.

2.2.2 Data Mapping

The scale and complexity of the classification framework made it difficult for us to extract meaningful information. Thus, we designed an interactive visualisation tool that allowed us to unveil and analyse the interrelationships among the dimensions (or clusters).

As a first step, we selected the three most significant dimensions—*aims*, *terminology*, and *disciplinary areas*—and the related taxonomies, leaving the others out. This way, we both streamlined the analysis process and focused on the part of the data from which we could extract knowledge most relevant to our enquiry. Then, we defined a hierarchy among the three dimensions, choosing "aim" as the benchmark dimension to which cross-reference the other two. This means that we focused on visualising the aims-disciplinary areas interrelationships and the aims-terminology interrelationships separately. In other words, we decided to design the tool so that it was possible to cross-reference the taxonomies of both "terminology" and "disciplinary areas" to that of "aims", in two sperate stages. As a third step, we designed a graphical layout that maximised the understanding of the interrelationships among the dimensions. Based on this layout, we finally implemented an interactive tool that allowed us to switch among three distinct visualisations.

The first visualisation offers the reader an overview of all the types and sub-types of aim (see Fig. 2.2). In this layout, the little orange-colour bars indicate the number of literature sources per sub-type of aim. This way, one can clearly see that the most common sub-types of aim found in literature are "evaluate-analyse" and "test" (within "assess"), "convey" (within "communicate"), and "create-design" (within "develop"). Moreover, the visualisation reveals that the traditional way of understanding prototypes is prevalent among the literature sources analysed.

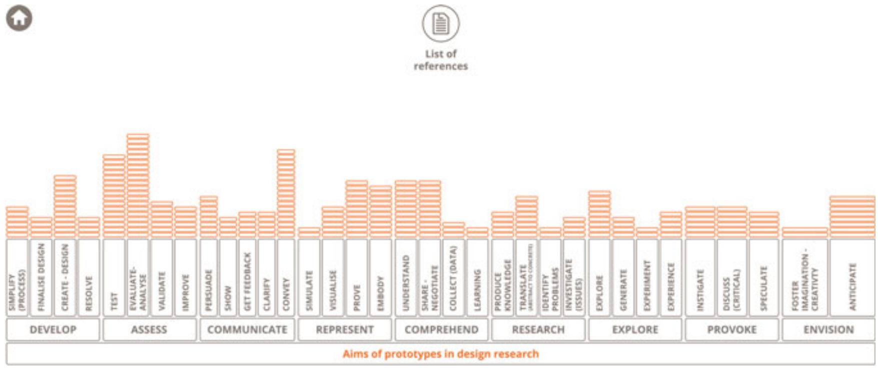

Fig. 2.2 Number of publications per type and sub-type of aim

The other types of aim are all extracted from about ten literature sources: “create-design” (within “develop”); “prove” and “embody” (within “represent”); “understand” and “share-negotiate” (within “comprehend”). Few types of aim were extracted based on only two publications: “simulate” (within “represent”); “learning” (within “comprehend”); “experiment” (within “explore”); and “foster imagination” (within “envision”).

This part of the visualization gave us the chance to gain an immediate understanding of the prevalent types and sub-types of aim among the literature sources. As an additional source of information, we added a link to the complete list of references—available by clicking a dedicated icon at the top of the screen page.

The second visualization reveals the aims-disciplinary areas interrelationships (Fig. 2.3). This part of the tool is interactive—by clicking on a specific disciplinary area, the related types and sub-types of aim light up in orange colour. Clicking on the icon “Show references”, it is also possible to access the literature sources related to the disciplinary area currently selected.

As shown in Fig. 2.3, almost all types and sub-types of aim relate to “industrial design”.

As for the disciplinary area “design fiction”, the types and sub-types of aim on the right are prevalent (Fig. 2.4).

“Mechanical engineering”, “industrial design engineering”, “computer engineering”, “product design”, “ubiquitous computing”, “human–computer interaction”, and “interaction design” are related to almost all types and sub-types of aim. On the contrary, “product engineering”, “product design”, “service design”, “critical design”, “design (arts and crafts)”, and “fashion design” only relate to a small part of the types and sub-types.

The last screen page shows the interrelationships between the dimensions “terminology” and “aims” (Fig. 2.5). The cluster “terminology” comprises six groups of terms (66 between types and sub-types). By clicking on the pushbuttons of the groups, it is possible to select the specific terms that the groups contain. Depending on the term selected, the related set of types and sub-types of aims lights up in orange

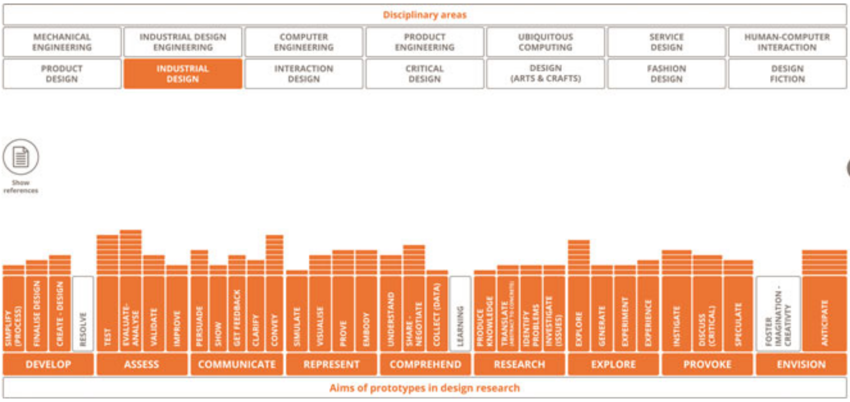

Fig. 2.3 Types and sub-types of aim relevant to the area of “industrial design” and the related number of publications

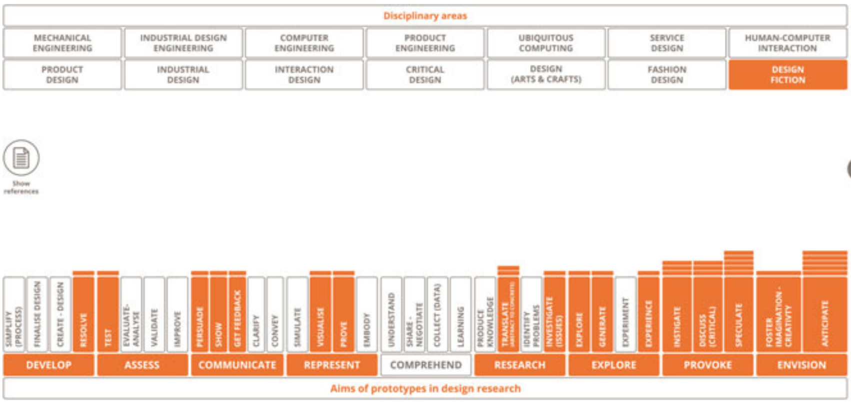

Fig. 2.4 Types and sub-types of aim relevant to the area of “design fiction” and the related number of publications

colour. Moreover, once selected, the term is linked—visually—to all the literature sources where that specific term was mentioned.

This interactive visualisation tool allowed us to observe and understand meaningful interrelationships among part of the clusters and taxonomies that structure our classification framework. Understanding such interrelationships complements the knowledge contribution offered by the framework.

It is worth to mention that the classification here presented is based on a limited dataset. The extant literature about prototypes in design research is most likely larger than the sample on which we based our study.

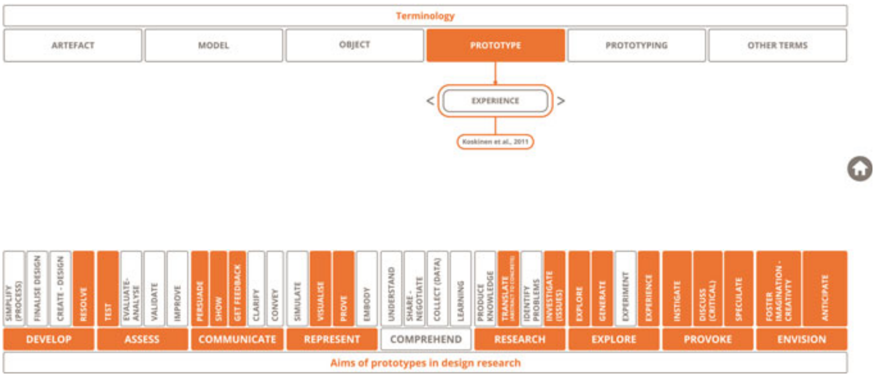

Fig. 2.5 Types and sub-types of aim related to the term "experience prototype"

2.3 Grounded Theory-Based Analysis

In addition to the classification framework, we developed a study based on the Grounded Theory (GT)—a well-established methodology in the field of social science, largely employed to conduct qualitative research (Chun Tie et al. 2019; Noerager Stern 2009; Wolfswinkel et al. 2013). Complementing our literature review with a systematic bottom-up approach, we believe, had the twin advantage of making the theoretical outcome grounded on data as well as opening the enquiry to serendipitous observations.

The GT process consists, by and large, of four stages of analysis, through which bits of raw data are progressively labelled, clustered, and interpreted, aiming to the development of a theory or multiple theoretical constructs (Fig. 2.6). This framework is the bone structure of all the genres of the GT methodology (i.e., *traditional*, *evolved*, and *constructivist* GT) (Bryant 2019; Chun Tie et al. 2019; Morse et al. 2009).

It is worth mentioning that in our study, we relied exclusively on extant data (i.e., secondary data collected from literature), which were sorted and distilled by means of the data cards earlier mentioned (see Sect. 2.1.3). These cards allowed us to sift through a large body of literature and thus to pinpoint the content most relevant to our subject of enquiry. In this respect, we applied GT to a pre-processed chunk of data—in particular, the section of the cards pertaining to the "role of the prototype"—streamlining the first stage of the analysis significantly.

Based on the classical structure of the GT methodology, we organised the analysis into four main stages (Fig. 2.7). The first three stages match the central threefold process of coding—*initial*, *intermediate*, and *advanced* (Chun Tie et al. 2019). In this regard, the only change made consisted in dividing the first stage into three steps, two of which were carried out by implementing a double-blind method, as explained in the next section. The remaining stages, on the other hand, patterned more closely the traditional framework of the GT.

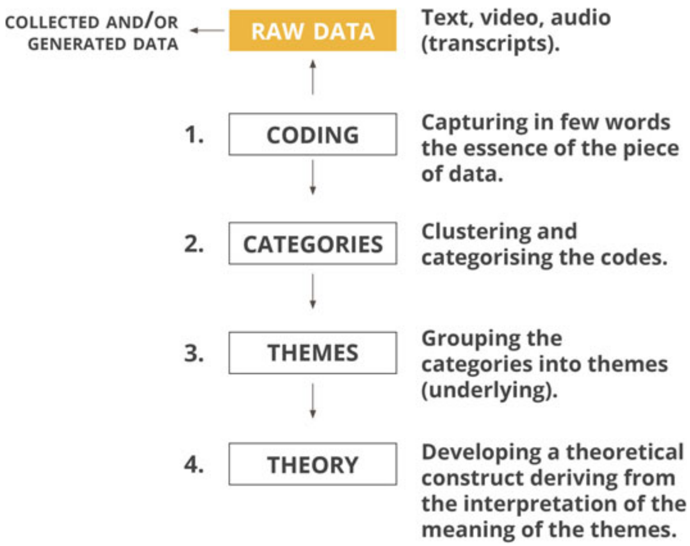

Fig. 2.6 Backbone of the GT analysis process

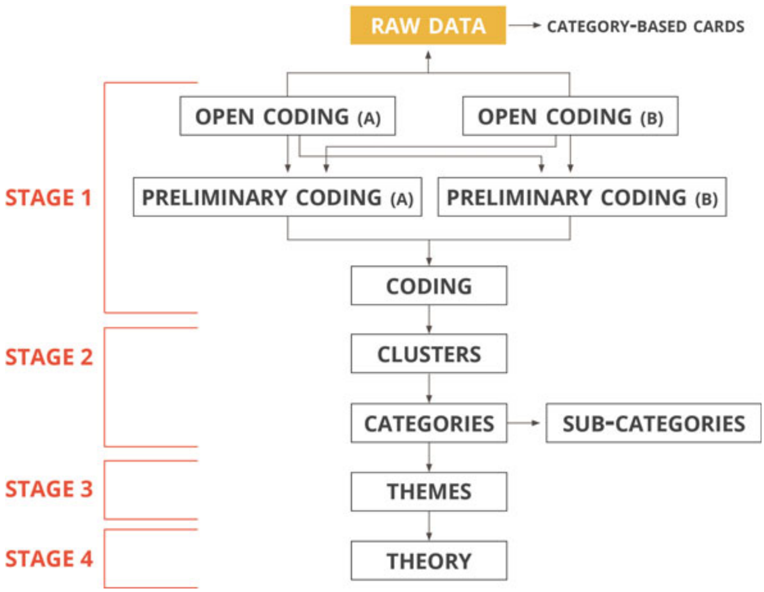

Fig. 2.7 Stages of the GT analysis process

In the next section, we provide a detailed account of the analysis process, step by step, as it was carried out.

2.3.1 Coding

At the core of the GT methodology, coding allows for the development of interpretive theoretical constructs that are grounded on data. This activity consists in attributing labels to raw data, either collected or generated, with the aim of capturing the underlying meaning and identifying recurring concepts. The labels, thus, serve as building blocks of a coherent plot, which structures the final interpretation of the phenomenon under scrutiny.

In the *initial coding*, the labels bear either single words or brief sentences, which are meant to both unveil and condense all the possible shades of meaning behind each piece of data examined. As earlier mentioned, we structured this stage of the process into three activities: (1) *open coding*; (2) *preliminary coding*; (3) *coding*.

We carried out the first two steps of coding by employing a double-blind procedure, aiming to make the outcome of the interpretation more trustworthy. This process proved preparatory to the actual (or definitive) coding, which was carried out based on the results of the double-blind labelling. To specify, the third activity consisted in openly verifying—and revising—the labels assigned to every single piece of data throughout the first two activities.

To summarise, we organised the first stage of coding—usually referred to as *initial coding*—into three activities, two of which were conducted following a double-blind procedure. The coding was limited to a specific section of the analysis of the cards prior developed. In particular, we focused on the section of the cards dedicated to the analysis of the aim/role of the prototype, as identified by the authors of the single literature sources examined (see Fig. 2.8). Overall, we processed sixty-three (63) cards, which match an equal number of literature sources. Below is a detailed account of the three steps of coding.

2.3.1.1 Open Coding

The first round of coding was deliberately designed to be carried out in a spontaneous and open fashion. The Cards were grouped into two packs and handled by two researchers—from now on resA and resB—in separate rooms. Thus, none of the two researchers could see the codes generated by the other. For each card, a maximum of five codes were assigned. Once the two researchers finished coding the cards assigned to them, they hid the codes generated by applying a mask of paper on each single card and swapped each other's packs of cards (see Fig. 2.9). Thus, the researchers proceeded with coding the remaining half of the cards. This way, resA and resB were able to rapidly code all sixty-three (63) cards in a blind mode (i.e., without influencing each other during the analysis process).

Johnson, B. D. (2011). Science Fiction Prototyping. Designing the Future with Science Fiction. Morgan and Claypool.

<u>Role/Aim of the prototype (as interpreted by the author)</u>

SFPs play the role of means by which to explore "the ramifications of new technologies, develop and test hypotheses, and find solutions to problems that come with pioneering techniques and emerging science." Prototypes are seen as stories that tell about the ultimate result in terms of features of the object/system but also in terms of context and social relationships that such an object/system is inscribed in or/and gives rise to ("Prototypes are not the thing, they are the story or the fiction about the thing that we hope to build") it to explain together what we hope to build.

<u>Categorisation criteria</u>

Aim: "[...] using multiple futures and realities to test the implications and intricacies of theory. Additionally, the output of the science fiction prototype can feed information back into the science and technology development process (more info in Chapter 7), investigating and shaping how a user might encounter, explore and ultimately use that technology" "We then use these fictions to get our minds around what that thing might one day be and we also use".

Discipline: Mainly Engineering (software/hardware engineering, computer science, ubiquitous computing) but also Industrial and interaction design (although it refers more to technology development).

Terminology: Science fiction prototyping (a means to more holistically envision the future development of technology).

Context: Industrial development oriented academic research (he worked at Intel and collaborated with organisations and companies as a futurist; but he is also a prof. at Arizona State University).

Fidelity: There's no reference to the concept of fidelity. Remains, though, the reflection about the fact that "closeness to what it could be like" is a key point of SFPing and therefore fidelity might be implied.

Phase (process): Throughout the process, employing a diversity of means (e.g., comics, short fiction, film). Actually, the framework proposed it is a process itself (structured in 5 steps).

<u>Author's specific distinction(s) (to be highlighted)</u>

SFP framework consisting of 5 steps + specific definition.

Fig. 2.8 Section of the cards analysed using the GT method

Fig. 2.9 Open coding: two-stage double-blind process

2.3.1.2 Preliminary Coding

Advancing in the analysis process, the codes produced in the first round of labelling were carefully examined and taken as a reference to generate one further code. The latter had the purpose of capturing the core meaning among those who emerged during the first stage as well as making a whole out of the many codes. In this regard, what we defined as *preliminary coding* may be regarded as a thoughtful re-coding of the first codes generated. In doing so, we refined the initial outcome of the analysis while setting the stage for the third and final step of coding.

Except for the higher degree of thoroughness, the preliminary coding patterned the procedure followed in the first coding round. Thus, resA and resB processed all cards separately, remaining oblivious to each other's coding results up to the end of the activity (Fig. 2.10).

2.3.1.3 Coding (Definitive)

At this stage of the process, each card contained two main codes—i.e., a summary of the various codes generated in the open coding phase. As a conclusive activity, resA and resB thoroughly examined the couples of codes, intending to generate an all-comprehensive code for each card. This activity was carried out by the two researchers, openly discussing about the outcome of the previous rounds of coding.

Fig. 2.10 Preliminary coding: two-stage double-blind process

By assigning one single code per card, we aimed to facilitate the transition to the following stages of the analysis (i.e., *intermediate coding*). On the other hand, we believed that it would be beneficial for the study to attain this result through a structured process, making sure that the final codes summarising the meaning of the cards reflected, as far as possible, the data that the latter contained. Moreover, by preserving the labels of all the coding rounds, we were able to keep track of the entire process of analysis. By doing so, we made the interpretive process intelligible (i.e., explicit) and thus possibly verifiable, coherence-wise, after its completion (Fig. 2.11).

2.3.2 *Categories and Sub-categories*

After coding all the cards, we worked together to identify recurring subject matters and cluster them into categories. The process consisted of two steps. First, we

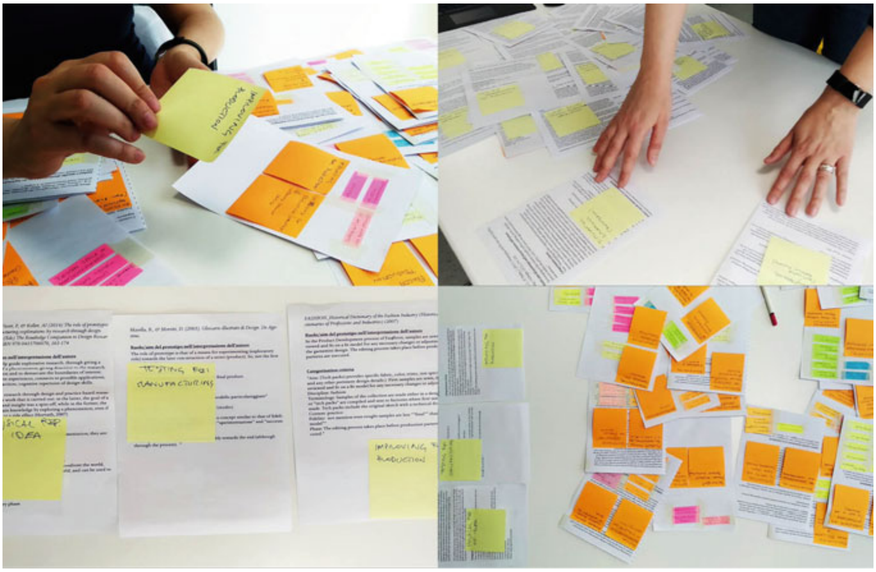

Fig. 2.11 Coding (definitive): summarising the outcome of the preliminary coding

sorted the cards into separate piles, following a first sketchy identification of similar patterns (Fig. 2.12). Once satisfied with the clustering, we labelled each pile with a code that summarised the dominant subject matter of the single cluster in one sentence. Overall, the classification yielded five (5) categories (Fig. 2.13).

After the classification, as the categories needed to be general enough to hold together relatively heterogenous groups of codes, we realised that some shades of meaning seemed to have been left out. Hence, we decided to create 2–3 sub-categories for each cluster. That way, we were able to do justice to the different thematic nuances within the single clusters while condensing the outcome of the analysis toward general theoretical constructs (Fig. 2.14).

It is worth mentioning that the physical manipulation of the cards proved crucial for successfully categorising the codes. Indeed, only when the labels were physically stuck to the pile of cards—making evident to which specific category each card belonged—were we able to assess the internal consistency of the single clusters.

Several reallocations and the very identification of the sub-categories followed this step. The five categories and related sub-categories follow.

- CAT.1 TESTING AND OPTIMIZING FOR PRODUCTION (MANUFACTURING)
  - Sub-cat.1 > Theory making and methodology integration
  - Sub-cat.2 > Developing design concept (through making/practice)
- CAT.2 MANIFESTATION OF DESIGN IDEAS

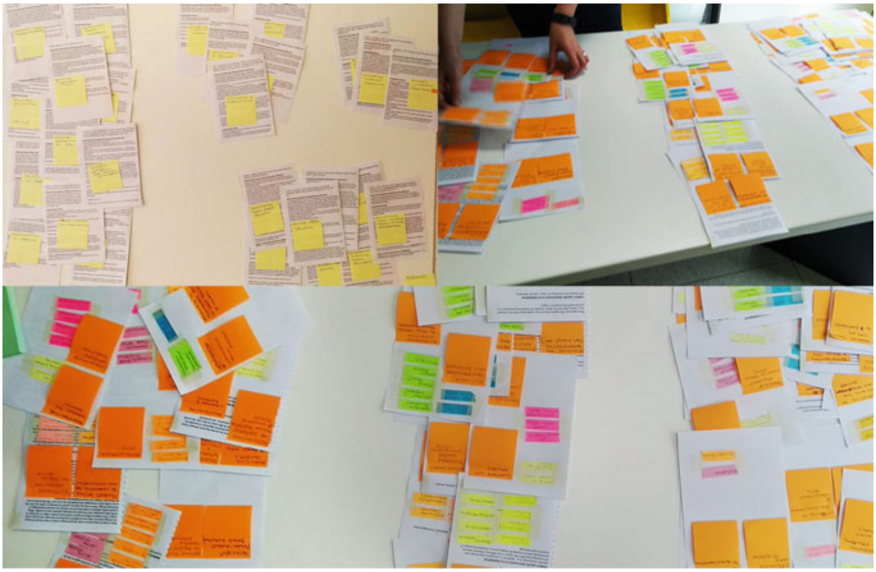

Fig. 2.12 Clustering the cards by subject matter

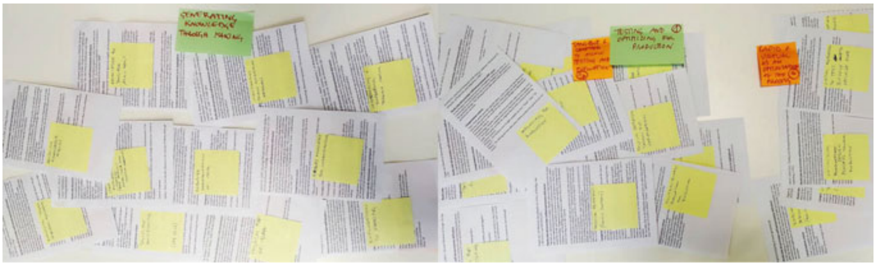

Fig. 2.13 First and second step of categorisation

- Sub-cat.1 > Manifesting to progress
- Sub-cat.2 > Physical representation of design ideas
- Sub-cat.3 > Experience manifestation for testing interaction

• CAT.3 GENERATING KNOWLEDGE THROUGH MAKING

- Sub-cat.1 > Tangible and crafted to allow testing and evaluation
- Sub-cat.2 > Rapid and virtual as an optimization of the process

• CAT.4 REPRESENTING POSSIBLE DESIGN SOLUTIONS THROUGH SPECULATIVE FICTION

- Sub-cat.1 > Envisioning through tangible and interactive speculation
- Sub-cat.2 > Envisioning through abstract (imaginative) speculation

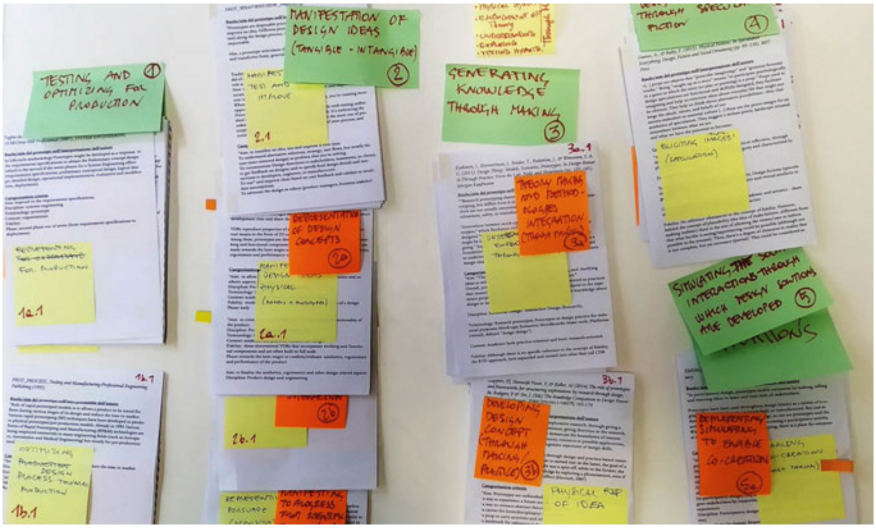

Fig. 2.14 Overview of the categories and sub-categories that emerged

   – Sub-cat.3 > Envisioning through non-fictional speculation

- CAT.5 ENACTING SITUATIONS
   – Sub-cat.1 > Representing/simulating to enable co-creation
   – Sub-cat.2 > Simulating to foster service development

2.3.3 Themes

Identifying broad and conceptual themes underlying the groups of codes and categories is a crucial step toward the development of theoretical constructs. This stage, usually called advance coding, allows for linking descriptive and data-driven categories to abstract and theoretical concepts. The themes, in this respect, are meant to condense the manifold strands of meaning that punctuate the categories into general and abstract terms (Fig. 2.15).

Working along this line, we identified 13 broad themes:

T1 > MAKING DESIGN THEORY THROUGH PROTOTYPING
T2 > TRANSITION FROM ABSTRACT TO CONCRETE
T3 > TRANSITION FROM VAGUE TO CLEAR
T4 > PROTOTYPING AS A MEANS FOR REFLECTION
T5 > EVOLUTION IN THE WAY PROTOTYPES ARE MADE
T6 > PROT. TO UNDERSTAND THINGS SITUATED OUTSIDE
T7 > PROTOTYPE IS NOT ONLY AND ANYMORE PHYSICAL
T8 > PROTOTYPING AS A MEANS TO UNDERSTAND THE PROTOTYPE

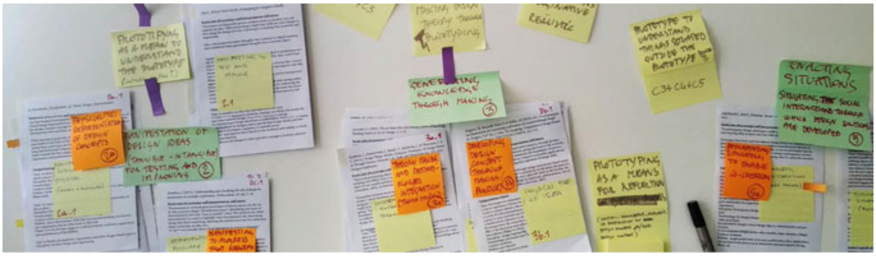

Fig. 2.15 Abstracting and conceptualising: identification of underlying themes

T9 > MERGING OF DIVERSE EPISTEMOLOGICAL APPROACHES
T10 > OPPOSITE DIMENSIONS—IMMAGINATIVE VERSUS REALISTIC
T11 > TRANSITION FROM VAGUE TO DEFINED (NO MATERIALISATION)
T12 > BLEND OF DISCIPLINES AROUND "DESIGN RESEARCH"
T13 > "ACADEMISATION" OF THE DESIGN FIELD.

The number of themes reflected a satisfactory abridgment since we considered both categories and sub-categories while abstracting and conceptualizing. Moreover, the emerging themes revealed a deep look at a variety of timely topics, highly relevant for many areas of design research.

Figure 2.16 illustrates an overview of the interconnections among the main categories and the underlying themes. As shown by the diagram, each category gave rise to multiple themes. Although not highlighted in this picture, the sub-categories proved crucial for the identification of the broad themes.

2.3.4 Theory

In the last stage, the themes were clustered into four abstract concepts. These crystallise interpretive theoretical constructs, which hinge upon the content of the very themes. Thus, the theory interprets wide-ranging phenomena to which the themes relate, beyond the single subject matter that emerged from the data. It is worth to notice that in some cases, the theoretical constructs were developed starting from an oppositional relationship between two themes. In this respect, the theory builds upon an articulate combination of groups of themes. That is to say, the relationships among the themes clustered under one umbrella concept can be both of oppositional and complementary type.

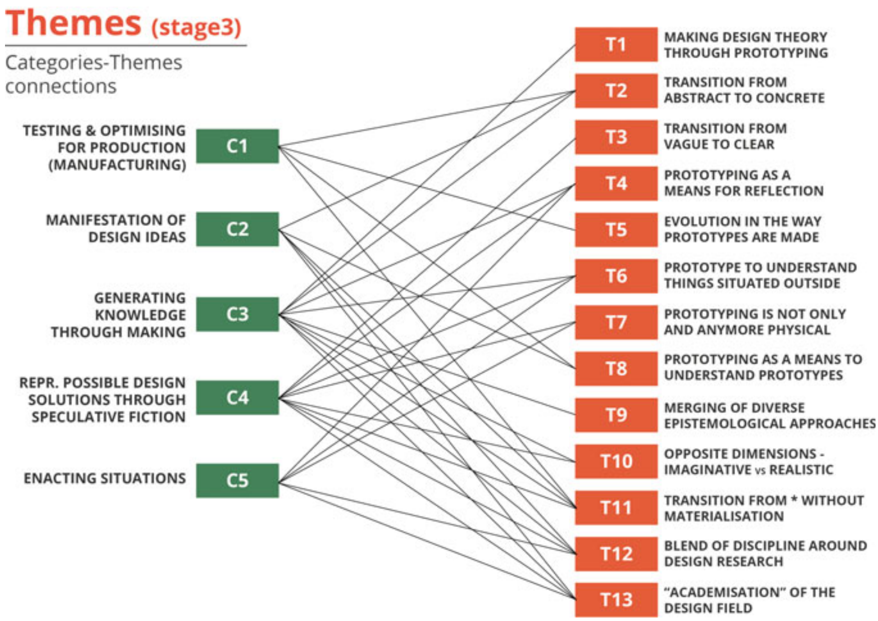

Fig. 2.16 Interconnections among categories and themes

2.3.4.1 Theoretical Concepts

Concept 1 "Transition"

- T2 Transition from abstract to concrete.
- T3 Transition from vague to clear—through fiction.
- T7 Prototype is not only/anymore physical—social interaction can be part of it.
- T10 Opposite dimensions: Imaginative versus Realistic.
- T11 Transition from vague to defined, faint to detailed, internal to external without materialisation.

The role of prototypes in design research is mostly defined by the general function of representing ideas, namely, giving intelligible form to undetermined and abstract concepts pertaining to design solutions. Such a principle of transition from vagueness to clarity characterizes all views on the role of prototypes which dot the diverse landscape of design research. Whether it is practice-oriented research (e.g., R&D context) or academic research, prototypes in the field of design serve the fundamental need to make magmatic and conceptually embryonic ideas manifest through fathomable forms of representation. However, the recent growth and diversification of academic research have brought opposite interpretations regarding how such forms of representation should be understood and, above all, whether tangibility should be a decisive factor in this regard. The latter position is expressed by that set of research avenues following a research-through-design approach. With different slants and objectives, more traditional strands of research (e.g., product development-oriented research) stand on the same side. In both above-mentioned research areas, the transition from vagueness to clearness is considered fulfilled when moving from abstractness to concreteness, favouring tangible representations and the related-making process. On the opposite side stand those researchers who advocate fiction as a means to represent design ideas as well as the wide sector of service design research, which largely manipulates intangible things (e.g., policies). In the latter cases, unlike in the former ones, representation is understood as being abstract and imaginative. In this view, the transition from vagueness to clearness need not materialisation to be accomplished. Rather, speculation is deemed more appropriate than physical construction and testing, with particular regard to the capability of envisioning solutions to complex problems. Overall, although the whole field of design research intends and employs prototypes as means to make ideas manifest, moving from vagueness to clearness, the way such a form of representation (i.e., making ideas manifest) is understood and achieved varies depending on the research areas, to the point of generating opposite poles: speculative and intangible on the one hand, material and realistic on the other. Such a dialectic tension, to conclude, shows how physicality is no longer a fundamental requisite for the prototype to be deemed as such. In this respect, prototypes can be intangible and imaginative as long as they give a prototypical form to the design ideas being developed.

Concept 2 “Making Theory”

- T1 Making design theory through prototyping.
- T2 Transition from abstract to concrete.
- T4 Prototype as a means of reflection: critical/speculative/evaluative reflection on the design process or/and design content.
- T6 Prototype to understand things situated outside and related to it.

Besides traditional testing, validation, and verification of production requirements, the prototype has taken on the role of means to reflect on both the design process and the phenomena pertaining to the psychology of users. Such a new way of conceiving prototypes in the design process has been put forward by new strands in the field of design research, such as service design and research-through-design oriented research groups. While the latter’s endeavours are strongly devoted to reflecting through making, favouring physical prototyping, the former’s serves social interaction and intangible forms of representation. In both cases, however, emphasis is given to ‘trying out’, aiming to understand conceptual aspects related to the way users interact with the object, system, or service being designed. These aspects are not necessarily related to the prototype itself, meant as an infant version of a specific product to be developed in the near future. Indeed, these aspects relate to the being-constructed prototype only to the extent that such a prototype allows for an actual verification of the assumptions made with respect to the related users’ behaviour, in view of a possible generalisation. In other words, the specific prototype(s) become proxies of theoretical instances to be put to the test in order to understand the dynamics related to the use of, e.g., materials, technologies, and social interactions. Understanding such dynamics allows for the development of theoretical frameworks to be employed in the design of future products. Evidence of this is that, in the above-mentioned research areas, often the prototype does not embody a to-be-developed product at its early stage of advancement. Conversely, a prototype of this kind embodies parts of a potential product—to be developed in an undefined future. Such parts are tested with the aim of identifying abstract patterns that can be turned into design guidelines for the design of possible future products, so contributing to the making of theory. Overall, making theory through prototyping is the most significant aspect of a new way of understanding the role of prototype in the field of design research, whether purely academic or practice oriented. This conception sees prototypes as means to understand and verify aspects pertinent to things situated outside of the prototype and yet related to it (e.g., how the user's behaviour varies when the material is changed). These aspects are tested to make generalisations that prove applicable to the design of possible future products. Moreover, this idea of using the prototype to generalize theoretical principles to be applied to different products is more important than—although not independent of—the idea of understanding through making (materializing).

Concept 3 "Evolution"

T5 Evolution of the way prototypes are produced.
T6 Prototype to understand things situated outside and related to it.
T8 Prototype as a means to understand the prototype.
T12 Blend of disciplines around "design research".
T13 "Academisation" of the design field.

The role of prototypes in design has changed over time. Until the 1980s, they were likely high-fidelity models rich in aesthetic details. They were made at the end of the design development process to demonstrate how the final product would appear. They were used to check the product before production and discuss it with the client. In this context, prototypes were developed to represent and test concepts in a linear process, typical of New Product Development. A new product was devised and depicted by two-dimensional representations (sketches, drawings, etc.). Then, it was developed by making three-dimensional models. Developers used such models to describe the product's function, performance, and visual features. In this perspective, the prototype's role was to build knowledge *about the prototype itself* (its function, performance and look). While traditionally prototypes have been means to bring ideas to life before mass manufacturing, today, they are going through a radical change, just like the design discipline.

Indeed, the technological and digital revolutions have impacted the development of prototypes on several levels. On the one hand, with the introduction of new prototyping techniques (virtual and rapid prototyping), since the 1990s, making prototypes allowed for optimizing the whole design process. On the other hand, the digital revolution has boosted the development of new interactive electronic products requiring specific physical prototypes to investigate the user experience. These prototypes sometimes are just partially working; they display the visual feature and functions to test. Designers use them to focus on the experience rather than on the technical aspects of the design. Furthermore, these smart products are complex and require the coordination of several types of expertise (product design, interface design, electronic and software engineering, etc.). Thus, the design process of such products has become more iterative than linear—all sorts of prototypes are made throughout the development process for testing and redesigning different aspects. Several disciplines gather around this process, merging different methodologies and competencies. This evolution occurred at the industrial level, in R&D departments, and in practice-oriented academic research.

In the meantime, in academia, new roles of the prototype emerged in parallel with the development of novel approaches to design research. Indeed, in the context of product development, prototypes—no matter how advanced—are made to reach an understanding of what is being developed (i.e., prototypes as products-to-be), whereas in academic research, prototypes are often used to generate new knowledge, that is, to reach an understanding at a higher general level that goes beyond the product under development (*beyond the prototype itself*). The underlying concept is that the creative act of *making prototypes* is itself a potential generator of new knowledge. Moreover, in (academic) design research, prototypes can be used to manifest immaterial aspects of the systems being designed—e.g., enacting a situation to test a service or envisioning solutions through speculation (tangible and interactive/abstract, fictional or non-fictional).

Concept 4 “Milieau”

T1 Making design theory through prototyping.
T9 Merging of diverse epistemological approaches.
T12 Blend of disciplines around “design research”.
T13 “Academisation” of design discipline/field of study.

The role of the prototype has evolved hand in hand with the context in which it is applied. In this regard, the development of design research as an academic discipline marks a fundamental step in the process of evolution of the role of the prototype. Indeed, since the foundation of design as a discipline, design researchers have worked on structuring consistent methodologies and epistemological approaches, reinterpreting the role of prototyping under a different light. According to one view, prototyping is understood as a cognitive repertoire of design skills, used by researchers to carry out exploratory research. The latter hinges upon the physical representation of design ideas, which elicits reflections and discussions, allowing for the assessment of the generated design concepts from the part of the different experts involved in the research process. This way of understanding the role of the prototype implies the idea that design can generate knowledge through making—i.e., developing theory by making, testing, and evaluating tangible representations of design concepts. In this respect, the research-through-design approach entails the use of prototypes as part of a process that is highly iterative, interdisciplinary, and based on the integration of different methodologies (which often are derived from other disciplinary fields). According to a different perspective, a distinction must be drawn between research through design and practice-based research. The distinction lies in the nature of the aim of the prototyping activity. To specify, in practice-based design research, prototyping serves the development of one or more products, whereas in the RtD approach, the ultimate goal of the prototyping activity is that of gaining knowledge by exploring a phenomenon. Hence, in practice-based research, prototypes are used to better understand what is being developed in the design process. In RtD, on the other hand, prototypes are employed to produce theoretical knowledge, beyond the very development of the prototype.

Furthermore, design research has expanded into areas such as service design, participatory design, and design fiction, where the concept of "generating knowledge through making" refers to both material and immaterial artefacts. These artefacts can play different roles: from simulating situations to enabling co-creation or fostering service development to representing possible design solutions through speculative fictions. In the latter case, artefacts support the process of envisioning through tangible and interactive speculation, abstract (imaginative) speculation, and non-fictional speculation. In this perspective, prototypes may be either physical objects or videos or written stories as the purpose is more relevant than the quality of the features. Indeed, the aim of prototypes and prototyping, in this view, is that of envisioning possible futures to be investigated through designing, regardless of feasibility issues.

In conclusion, as far as prototypes are concerned, the process of "academisation" of design has led to a change of purpose. Compared to the traditional use of prototypes in design practice—from small design studios to R&D sections of large companies—today's role of prototypes in academia is of higher complexity and abstractness. Prototypes, in this context, are developed to elicit discussion and reflection, test theories, and generate new theoretical knowledge.

2.3.5 Making Data Digital by Qualitative Data Analysis Software

As earlier mentioned, the physical manipulation of the data in the form of cards proved crucial for the successful development of the analysis process. On the other hand, software for qualitative data analysis is of great use when storing the data and visualising the analysis process. Moreover, such software allows for a fast double-checking of all stages of the analysis. Therefore, we decided to digitalise the entire analysis process, generating files based on manual coding. Below an example of the digital processing of data using the software MAXQDA (Fig. 2.17).

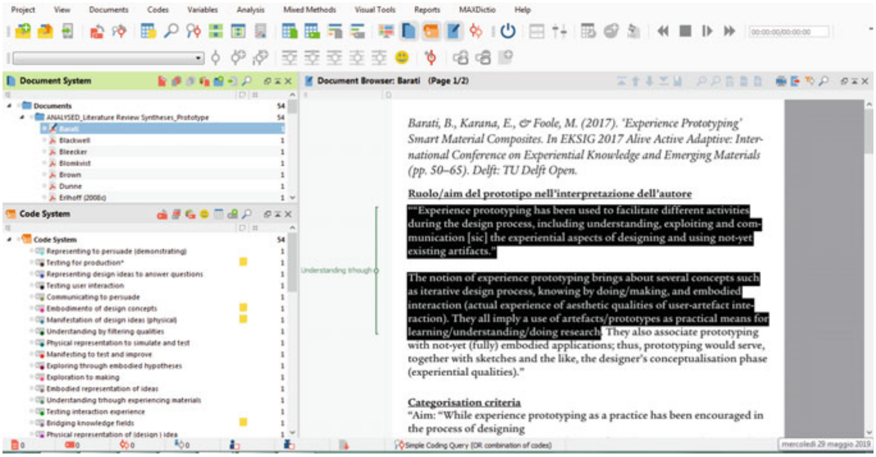

Fig. 2.17 An example of the digital processing of data using the software MAXQDA

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Chapter 3
Making Use of the Research Framework

Silvia D. Ferraris and Francesco Isgrò

Abstract The main objective of this research phase was to validate the findings of the first part of the research and to develop a framework for the role of prototypes in design research. We decided to validate our results by sharing them outside our research group to gather feedback and deepen the discussion. Thus, we interviewed nine researchers and practitioners in the design field. We shared our four theoretical concepts with them and collected their opinions, which we later shared among the research team members. Additionally, we asked the interviewees to share a case study of one of their research projects where the prototype played a relevant role. We asked for a short description of the research and prototype using the set of categorization criteria developed in the analytical phase of the study. The collection of these data proved to be valuable and complex. We anticipated the existence of interesting relations among the criteria. Therefore, we made an interactive visual tool that enabled us to discover and highlight such relationships. For instance, we highlighted the relationship between the context and research aim or between the prototype's nature and the research phase. Eventually, as a discussion tool, it let us observe our data and elicited further debate. Through this research phase, we developed our general understanding of the phenomena.

3.1 Case Studies Framed Through an Interactive Tool

3.1.1 Setting the Second Phase of the Research

The main objectives of this research phase were to validate the findings of the first part of the research and to develop a framework for the role of prototypes in design research.

The findings of the first part can be summed up in:

- There is no universal definition of the prototype in the design community.

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- It is possible to define a prototype through a set of categorisation criteria (aims, discipline, terminology, context, fidelity, phase of the process).
- Traditionally the role of prototypes is to support the production of specific knowledge *about the prototype itself* to support the design process.
- In design research today, prototypes also support the production of theoretical knowledge *beyond the prototype itself*.
- Four theoretical concepts synthetize our understanding of the relevant phenomena that concern the role of prototypes in research today "Transition," "Making theory," "Academisation," and "Milieu" (see Sect. 2.3.4).

We decided to validate our findings by sharing them outside our research group and gathering feedback and case studies. We planned interviews with nine researchers and practitioners in the design field. We shared the four theoretical concepts with them and asked their opinion on our findings using a list of given questions. Then, we shared the outcome of the interviews among the research team members.

Also, we asked the interviewees to share with us, if possible, a case study of one of their research projects where the prototype played a relevant role.

At first, we asked them where they worked, proposing to option among four contexts ("Practice," "Practice + Research," "Research + Practice," to "Academia", as defined in Sect. 2.1.2). Reflecting on this request, some interviewees told us that they worked across two of them. We recorded this input for further discussion on the relevance of the context in which the research takes place.

Secondly, we asked which disciplinary area they identified their work, and we let them give open answers. These questions helped us frame the context where the case study took place.

Thirdly, we asked for general information about the project research, such as name, period, other partners or people involved, and their role in the project/research.

Fourthly, we asked for a short description of the project research focusing on the role of prototypes in it. In addition, we used the set of categorisation criteria (defined in Sect. 2.1.2) to collect data about the case study. Thus, we asked:

- About "Terminology": all terms they remember using other than "prototype."
- About "Phase of the process": if they applied the prototypes in a specific phase of the process (giving the option among "conceptualization," "design development," "detailing," and "before production", as defined in Sect. 2.1.2);
- About "Fidelity": if they used this concept when describing their prototypes (giving the option among "low," "medium," "high," or "implicit," as defined in Sect. 2.1.2);
- About the "Aims," we gave them our list of aims and sub-aims (see Sect. 2.3.1) and let them select the ones that applied to make their prototypes.

Hence, the data collection format strictly referred to the criteria we identified during the literature review.

3.1.2 Selection of Interviewees and Case Studies

All the authors contributed with their research interests and specific disciplinary point of view in the research. As said, we all share an interest in product design, its material aspects, and its interaction with the user. Some researchers are interested in fictional or experiential approaches (see Chap. 5). Some are interested in interactive aspects of product design (see Chap. 4). Some focus on industrial design, design innovation, and design engineering (see Chap. 6).

We do purely *academic* research and research with external partners (industrial, public, etc.). Thus, as regards our definition of the context, we belong to "Research + Practice" and "Academic Research" (Sect. 2.1.2).

Hence, we selected nine experts from research universities and design consultancies to collect academic and not academic input, as planned from the beginning. Hereafter we introduce them briefly to explain the analysis and framework, while more extensive descriptions and insights will follow in Chaps. 4, 5, and 6.

Case Study 1. Interviewee: Sara Colombo, Ph.D. At the time of the interview, she was a research project lead at MIT Design Lab. She is now an Assistant Professor at the Eindhoven University of Technology, NL

Disciplinary Area: Design

Context: Research + Practice and Academic Research

Research: "Augmented Health and Safety: Future Vision"

In Brief: This project was developed in collaboration with a worldwide energy company. The aim was to foresee how emerging technologies might integrate the energy industry's health and safety approaches. The near future vision would support change and encourage the development and adoption of innovative solutions. The design fiction approach chosen for the research was based on designing and prototyping an ecosystem of physical and digital solutions. These new technology-based designs anticipated a vision of managing health and safety practices in future scenarios and triggered discussion among all stakeholders (Colombo et al. 2018). This research presents an example of the collaboration between an academic research center and an industrial partner to develop a new vision through design fiction.

Case Study 2. Interviewee: Marco Meraviglia, Cefriel S.Cons.R.L. Milan

Disciplinary Area: Design and Engineering

Context: Practice + Research

Research: "Hemomix MILANO"

In Brief: The project aimed to develop a new device for blood collection monitoring. The tool monitors the safety and the steps of the donation. It has a scale function, weighing the collected blood, and a mixing function that avoids blood coagulation. The project was done in collaboration with the company Delcon to meet the requirements of the New York Blood Center. The user-centered approach enabled the designers to make a new concept worth the Compasso d'oro Award in 2022. This research presents an example of the collaboration among three parts: design and engineer experts, the industrial developer, and end users (the medical center in this case) to develop an innovative industrial product.

Case Study 3. Interviewee: Bastien Kerspern, Co-Founder of Design Friction, Nantes, France

Disciplinary Area: Design Fiction and Speculative Design

Context: Practice + Research

Research Project: "The Rules for the Game for the Smart Streets"

In Brief: Performing a prospective crash-test of citizens' recommendations framing smart street experiments to adapt these propositions of rules in return. This research was conducted in the form of three organized workshops involving citizens and participants from local areas. This participatory approach ambitioned to collectively define a set of recommendations regulating the experiments of new technologies and new uses taking place in the public space on Nantes Island. This methodology of prospective and critic evaluation demonstrates how this design fiction approach can participate in a more extensive collaborative innovation process. This research (Design Friction n.d.) also presents an example of the collaboration between a design consultancy and an urban planning and development bureau.

Case Study 4. Interviewee: Pieter Jan Stappers, Professor of Design Techniques at Department Industrial Design, section Conceptualization and Communication, TU Delft, the Netherlands

Disciplinary Area: Design Engineering

Context: Research + Practice and Academic Research

Research: Keller's TRI and CABINET Ph.D. Thesis "FOR INSPIRATION ONLY. Designer Interaction with Informal Collections of Visual Material" by Adriaan Ianus Keller

In Brief: This research looked at how designers collected visual materials to inspire their design process. The aim was to support designers in this process by combining electronic and physical images. To this end, the researcher developed two prototyped solutions: a platform for exploring design tools using a sketchy variety of virtual reality techniques and a tool that merges virtual and physical images into one seamless collection. The prototypes could be experienced dynamically and interactively; thus, they could be tested by users and actively used for research. Theory and practice were integrated into this process thanks to the application of working prototypes used as research means to demonstrate and explore theoretical hypotheses. The author reported and analysed the whole research project. Then he generalised his findings. This research represented a crucial example of both Research through Design and Research for Design (Stappers et al. 2014).

Case Study 5. Interviewee: Livia Tenuta, Ph.D. Assistant Professor, Design Department, Politecnico di Milano, Italy

Disciplinary Area: Fashion Design

Context: Research + Practice; Academic Research

Research: SmartJ. for Barakà

In Brief: The partnership concerned the creation of connected quantified-self bracelets for Barakà. This Italian company caters to a male audience based on jewellery references by applying a co-creation methodology between the fashion designer and the engineer's technology. The research included in four phases: brand study, encompassing formal and material aspects, product type and target audience hallmarks; market analysis and potential competitors; identification of existing technologies that could be combined with jewellery; development of a collection that includes scenarios for business as well for leisure. This research presents an example of collaboration between academia and an industrial partner (Tenuta 2016).

Case Study 6. Interviewee: M.Sc. Gabriele Diamanti, Co-Founder of ddpstudio

Disciplinary Area: Design

Context: Practice

Research: Hannes a Multi-jointed Prosthetic Hand

In Brief: Hannes is a prosthetic hand developed as part of a collaboration between the Prosthetic Center of INAIL and the Italian Institute of Technology. It's a new concept of a poly-articulated hand, able to restore over 90% of lost functionality in people with a limb amputation. One of the main aspects of innovation regarding competitors is the achievement of naturalness of forms, movements, and orientation of the rotation axes and hand postures. The thorough study of the anthropometry of the actual hand has guided the prosthetic hand design, from the aesthetics to the mechanical and structural features, allowing the user to perceive the prosthesis not like an external instrument but as an integral part of the body. Hannes received the Compasso d'oro Award in 2020.

Case Study 7. Interviewee: Olga Noronha, Ph.D., visiting lecturer at Royal College of Arts and Central Saint Martins. Artist based in Portugal and UK

Disciplinary Area: Jewellery Design, Art, and Science

Context: Practice and Research + Practice

Research: "Medically Prescribed Jewellery//'Becoming the Body': An Investigation into the Possibilities and Affordances of 'Medical Jewellery'"

In Brief: This doctoral research investigated the social and psychological aspects of body modification and medical interventions on and in the body by analysing biomedical research into the repair of the body, surgical procedures, material compatibility, and prosthetic design. The researcher outlined the theoretical underpinnings of the work, the necessary practice-material considerations in producing 'viable' medical jewellery, and the understanding of its reception in different contexts (medical and jewellery). The researcher made many prototypes that were materialising ideas and proposed them as possible futures. This way, she feedbacks from different publics and how it moves through and across other epistemic constructs (art and science). The research sought to minimise or deflect the negative effect of medical repair by developing new speculative designs made of aestheticised scientific technology and medical knowledge. These were used to investigate how they would be emotionally and physically experienced and what knowledge they would gather and convey. This study is an example of academic research.

Case Study 8. Interviewee: Tom Jenkins, Assistant Professor, IxD Lab IT University of Copenhagen

Disciplinary Area: Interaction Design

Context: Academic Research

Research: "Cohousing IoT"

In Brief: Cohousing IoT uses research through design to both alternative probe modes of living and prototype speculative domestic Internet of Things devices (Jenkins 2018). These prototype technologies are informed by a public design process that works in two ways. First, it imagines alternatives to existing arrangements of things and devices in the home; second, it produces prototypes that argue for new roles for internet-connected things that both support and sustain the social life of a cohousing community. This study is an example of academic research.

Case Study 9. Interviewee: Camilo Ayala-García, Assistant Professor, Universidad de los Andes, Colombia at the time of the interview, now Researcher at Free University of Bozen-Bolzano

Disciplinary Area: Materials for Design

Context: Product Design Research + Practice Academic Research

Research: CornStalk DIY-Material for Social Innovation

In Brief: Do-it-yourself (DIY) materials are an emerging field that has progressively gained attention because of its democratizing power and business potential. In this work, using cornstalk-based DIY materials to foster social innovation among Colombian small farmers is explored (Ayala-Garcia et al. 2017). This approach promotes a rural development that respects farmers' traditional practices and beliefs oriented towards collective progress and nature preservation. Hence, the theoretical review regarding social innovation, circular economy, DIY practices, and materials is tested by proving that corn stalk can be used as a raw material to make materials without the need for scientific knowledge, sophisticated technology, and polluting elements. In a second step, the theory and hypothesis were verified by interviewing Colombian farmers with whom the idea of using agricultural leftovers to produce DIY materials was shared and discussed during several workshops. This study is an example of academic research involving a local community for which the innovation was intended.

3.1.3 Analysing the Case Studies: An Interactive Tool

During the making of the interviews and case studies, we started to realize that the research and prototype's characteristics are related. For instance, the research's context and general aim might determine the prototypes' nature (virtual, digital, physical, etc.) or the specific aim for which they are made (assess, provoke, communicate, etc.). Still, we could not immediately find common rules that would define such relations. So, we decided to show those connections and see what they looked like. We developed a visual tool that would help us discover the relationships whose existence we could only suppose. Clearly, we were ready to find out that there were no recurring relations and rules.

3.1.3.1 Defining the Research Area

The purpose of this step of our study was to make evident relationships that we detected by reading and discussing the findings from the previous research steps. We imagined a visual area to place the case studies and point out the connections to all the categorization criteria (aims, discipline, terminology, context, fidelity, phase of process) we used in the literature review (Sect. 2.1).

The area would represent the characteristics of research in which case studies took place. So, first of all, we had to identify those characteristics.

Among the categorization criteria, we knew that the variants of the research that frame the role of the prototype are:

- The "context" and "disciplinary area" in which the researcher works.
- The "phase of the process" in which the prototype applies.

Furthermore, we realised that some critical input regarding the characteristics of the research area also came from the Grounded Theory study. In fact, among the four theoretical concepts, we thought the Concept "Transition" expressed some vital aspects to consider about the research features that frame the role of prototypes.

In Chap. 2, we said that the whole field of design research intended and employed prototypes to make ideas manifest, moving from *vagueness to clearness*. The way such representation is understood and achieved varies depending on the research areas, generating opposite poles: *speculative* and *intangible* on the one hand, *material* and *realistic* on the other (see Sect. 2.3.4.1). In the light of this reading, we emphasised that the research area could be defined as "speculative versus realistic" and "tangible versus intangible."

We defined "speculative" as the research that, as a general aim, poses open and reflective questions, elicits discussion, or prefigures possible futures, and supports the making of theoretical knowledge. For instance, we assumed a doctoral thesis would fall in this area.

Quite the opposite, some research's general aim is straightforward to develop and apply a new design solution, possibly right at the end of the research and development process, with not much time and resources dedicated to reflecting and sharing the results (both in terms of practical outcome and new knowledge). We assumed this is the case of research in R&D departments or design consultancy and, partially, in academic research developed with external partners. We called this research area "realistic" and later changed it to "concrete," trying to highlight the nature of the general aim of the research. Indeed "realistic" seemed as opposed to "fictional," which was not what we meant.

Regarding the feature of being "tangible versus intangible," we referred to the "object" of the research. So, if the research were about, for instance, the making of a new physical product or new material, it would be "tangible." In contrast, if the research were, for example, about a service, the object would be "intangible." We later change "object" into "essence" because the first implied an idea of materiality that we did not want to suggest. We knew that design research could focus on both qualities. For instance, a service might include the use of objects (i.e., a bike sharing service), or a device might imply interaction with Apps and other features that are more digital than physical (more software than hardware). In this perspective, research on interaction and experience design, where both physical and digital objects are applied, would cover both definitions. In our area, they would appear in between the definitions.

Ultimately, we decided to use the definition "speculative versus concrete" and "tangible versus intangible" to draw our ideal space to place the case studies. We thought this set of research characteristics could describe all case studies. In contrast, the context and phase of the research would be lateral information since we felt they were less relevant.

3.1.3.2 Defining the Prototype's Characteristics

For our visualisation, we had to highlight the prototype's characteristics that we wanted to emphasize. Again we selected them from the categorization criteria. The features that defined a prototype were "Aims" and "Fidelity." Most of all, we wanted to highlight the Aims because we understood that they are the most relevant feature that defines prototypes. While fidelity is not even cited or shared among the design community.

Furthermore, we recalled that—at a very general level, the role of prototypes in design research is to support the production of specific knowledge "about the prototype" and, possibly, to support the production of general knowledge that goes "beyond the prototype" itself. We planned to visualize this feature in our representation.

From making the case studies, we realized that it was helpful to detect also the "Nature" of the prototype. We distinguished three main possibilities.

First, the prototype is "Physical" when it can be experienced directly with one sense—typically sight and touch—and the other senses. We identify "physical" any tangible aesthetic and functional models, regardless of the level of fidelity, and any probs that imply a physical real (not virtual) interaction. Visual aids, such as paper prototypes, would fall into this definition too.

Secondly, the prototype can be "Digital" when it is a software part of the design (i.e., an interface) or it is a visual aid (based on digital technology), such as a video that shows a scenario or tells a story.

Thirdly, the prototype can be a virtual model tested in a virtual environment (that can be or not be immersive). Thus, we pointed out this feature "virtual environment" to point out that these virtual prototypes and environments enable a virtual experience that all stakeholders of the design process can use.

We noticed that in one research, prototypes of different "Nature" are present since they enable to reach different specific aims. Also, one single prototype can be physical and digital, i.e., a smart product with an App to use for interaction. At the same time, both a physical and digital solution can be experienced in a virtual environment. So, the option among "physical," "digital," and "virtual environment" is not exclusive.

Furthermore, we realized that in some specific research, prototypes are "fictional" as they represent something imaginary and pretend to be something else or something that might not even be possible nowadays. So, these prototypes do not embody something realistic yet. We called this nature "fictional" and pointed out that it can apply to the other three.

Regarding the categorization criteria "terminology" and "disciplinary area", we thought to keep this variable aside and check if we should integrate them later.

We developed a first rough paper model (Fig. 3.1) of the visual tool with all the variables of research and prototype characteristics.

We tested this first version with some examples from the literature review. We understood that even if it was promising, using all variables together was ineffective. Therefore, we simplified the concept and developed a digital interactive version of the tool. We thought an interactive tool would better support the visualisation of the relationships we were seeking.

3.1.3.3 Interactive Visual Tool 0.1

From the beginning, we decided that:

- The tool aimed to visualise possible relations between the research and prototype characteristics.
- The tool did not measure any feature or generate quantitative data.
- The tool was designed to support our understating of the phenomenon and elicit discussion with others.

We foresaw that, eventually, together with the first part research, the tool would let us define a general overview of the matter.

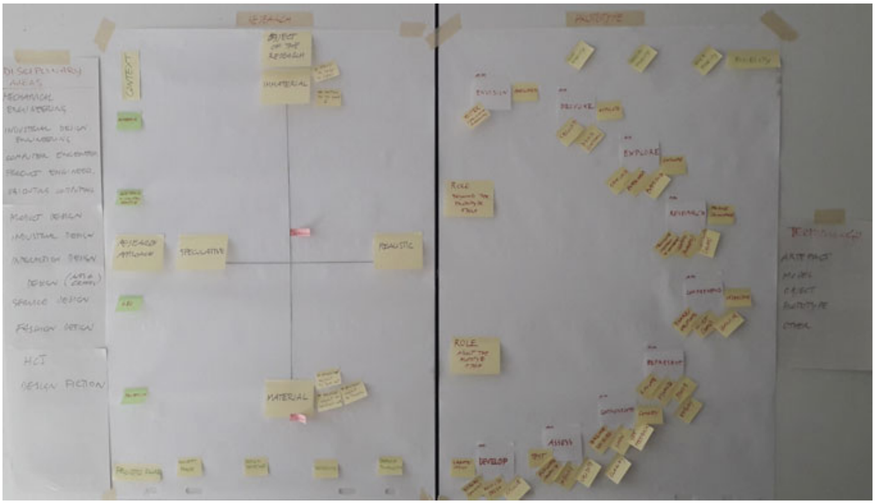

Fig. 3.1 First paper model of the concept of visual tool

So, we transformed the first paper model into a digital version of it. Later we reflected on the fact that even this study, which is purely theoretical, took advantage of the transition from abstractness to concreteness through prototypes (see Chap. 6).

First, we designed a Cartesian area (inside the orange square called "research") where the X-axis identifies the "essence" of the research from "tangible" to "intangible"; the Y-axis identifies the "general aim of the research." In this area, we placed a dot representing each Case Study.

The list of Case Studies is on the left side of this area. In the interactive tool, a sheet appeared when clicking on any of them. The sheet contained primary data about the Case Study (researchers, a short description of the research and its prototypes, disciplinary area, specific aims, and possibly an image). Also, every Case Study referred to a dot in the central research area. In this visualization a dot represented one research, and all the prototypes made and used within such research. The placement in one of the quadrants of the central area was qualitative. It indicated how "speculative versus concrete" was the general purpose of the research and how "tangible versus intangible" was the essence of the research.

To simplify, we decided to overlook the concept of "Phase of the Process" since, from the interviews, we realized that we could not find a process (and a finite number of phases) that was common to all research. Indeed, our first definition of four phases (conceptualization, design development, detailing, before production) worked well to refer to an "industrial product development process" with a quite standardized definition but was not proper for design research in general. So, we overlooked it also because not all authors mentioned it in the literature review.

In the tool, the characteristics of the prototype (aims, role, and nature) appeared around the central area in the larger grey square called "prototype."

To simplify, we decided to overlook also the concept of "Fidelity" since the design community does not equally adopt it.

The color defined the role of the prototype, from grey (about the prototype) to orange (beyond the prototype).

Each Case Study was connected to the prototype's aims, role, and nature in the interactive tool. So that it was possible to select one Aim (i.e. "Assess") and find out which dot appeared in the central area. This way, we could see which research/dot had prototypes made to "Assess." Also, it was possible to select other features, such as the prototype nature (i.e. "Virtual"), and discover which research used virtual prototypes.

In a general meeting, we used this tool version (Fig. 3.2) to check its validity. We discussed the first findings and then proposed some changes.

Some interesting relations were visible: the role of the prototype is "about the prototype" in "concrete" research, and it is "beyond the prototype" in "speculative" research. It was an assumption we already had in mind and confirmed by the visualization (grey dots are on the bottom).

On the contrary, we supposed that research developed outside academia would be all in the lower quadrant and vice versa, but that is not the case. Indeed, Case Study 3—a design fiction example by a design consultancy—appeared in the area's top (speculative) part.

All doctoral theses were on the top quadrant since they all had open questions and led to speculation, even when the object of investigation was very material. Yet, even

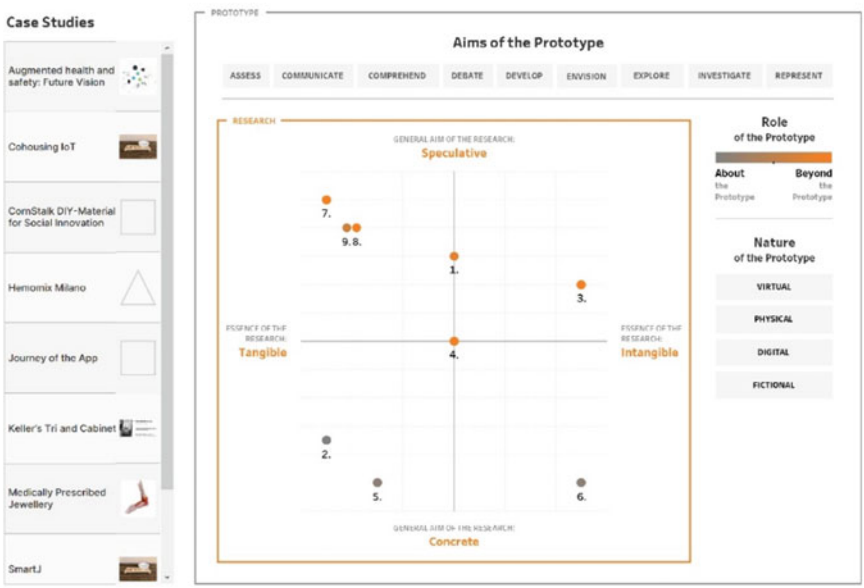

Fig. 3.2 First version of the interactive visual tool

research for a company, such as Case Study 1, appears in the top quadrants because it develops a fictional scenario to let the partner imagine what design solutions they could apply in their future.

The tool appeared interesting but with two significant weaknesses.

On the one hand, the selection of aims was not very effective because most of the Case Studies connected to most aims. So, the choice of one variable on the tool did not generate interesting visible connections.

We realised that this problem happened because we used the first level of aims (i.e., "assess"), not the second ("assess" contains: "evaluate, validate, improve"); also (see Sect. 2.2.1), we did not put any limit on the option of the aims; finally, for each case study/dot we combined the aims altogether.

On the other hand, we realized that placing all research prototypes together was an oversimplification. One dot would not represent the complexity of a research process where different prototypes are made and used for different aims in different moments.

We, therefore, decided to modify the tool.

3.1.3.4 Interactive Visual Tool 0.2

In the new version of the tool, we wanted to highlight the presence of different prototypes for different aims within the same research. For example, a researcher may apply a simple paper prototype for the first conceptual phase, a physical model for the second phase, and a virtual prototype for the last step.

Therefore, we asked the interviewees if the prototypes used in their case study may cluster in groups based on their roles in the research. We let them define the number of groups based on the specific aims they were made for. Thus, we asked to assign to each group one single specific aim. Finally, we asked to place them in the quadrant and define their nature—this way, each case study could be represented by a set of dots scattered in the research area. After a review of them, we realized that a few of them were still represented by a single dot. This case happened when prototypes in such a case study belonged only to one phase/aim.

We identify each case study with a number corresponding to one colour for better visual clarity.

Also, we introduced the information of the "context" in which the research took place as we realized it was an interesting factor to detect. We refined the definition, though, so the option ("Practice," "Practice + Research," "Research + Practice" to "Academia," as defined in Sect. 1.1.2) referred now to the context in which the research took place. So far, it represented the context in which the interviewee worked at the time of the interview, but this condition could have changed in the meantime. So, for interviewees who said they worked across two definitions, we picked the best representation of where the research developed. To make it easy to detect such information, we made different shaped icons instead of just dots (see the box "Context of research" in Fig. 3.3).

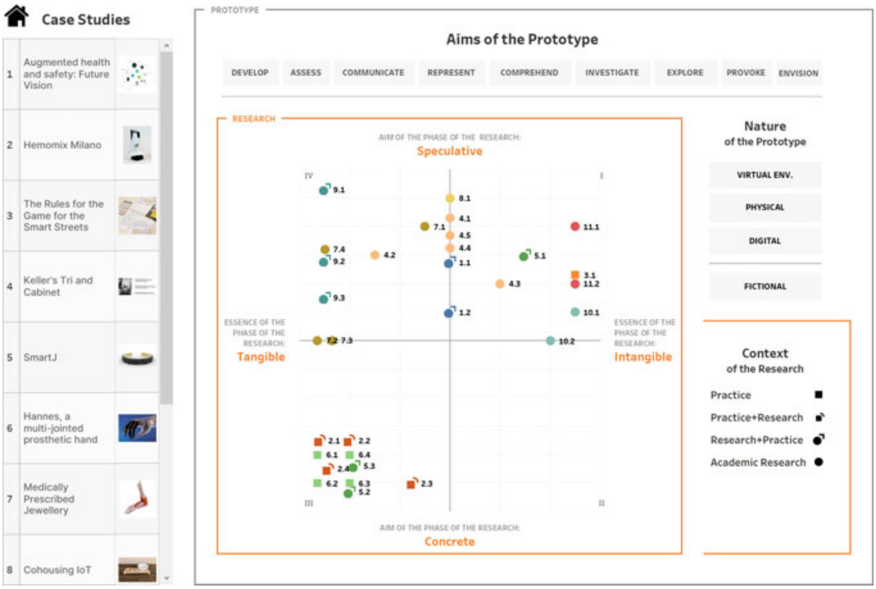

Fig. 3.3 Second and final version of the interactive visual tool

Finally, we decided to overlook the identifications of the role of the prototype "about" or "beyond" the prototype itself. Indeed, the first tool's version already proved our assumption, which was less interesting to get the overall picture.

This version of the tool proved to be more efficient in representing the complexity of the research and the role of prototypes. The selection among aims and groups of prototypes was more effective.

Eventually, after collecting the first nine case studies, we added two extra ones to check the appropriateness of the tool with research developed by us. We wanted to test the tool with case studies we knew in detail. We added:

- Case Study 10 The research "artificial intelligence in design" ongoing research about how to integrate AI in the creative phase of the product design process.
- Case Study 11 The study of this book "Paride. Advance prototypes for design research."

These extra examples helped to integrate the overview but, of course, did not cover all possible kinds of research in design. Of course, it could be possible to integrate it further to confirm the first reading or discover new relations. The readers may visit the website https://www.farbparide.dipartimentodesign.polimi.it/ and try the tool by themselves.

3.2 Visualising Relationships

While using the interactive tool, it was necessary to remember that:

- It is a *discussion* tool made to observe phenomena and elicit further debate. The assignment of a place in the quadrant was relative. Thus, the tool was not made for measurements or gathering quantitative data.
- It visualized only prototypes' features concerning the research they are made for. It did not represent the whole research process. Any research phase that did not use a prototype would not appear in the tool.

So, we looked at the Case Studies' visualisation and realised some phenomena.

3.2.1 Reading the Whole Picture

First of all, Quadrant II, "intangible-concrete," is empty. We realized this has to do with the group of research's interests and contacts, mainly about product design, design interaction, materials, design engineering, and fashion design.

Indeed, the tool was designed after the literature review findings, which covered any design research area. Thus, the tool could enclose case studies from any field, while we collected examples only from our specific areas. Should we want to fill Quadrant II, we should ask some communication design experts to participate in the study.

Secondly, we noticed that the academic research (rounded dots) was placed mainly in the speculative area (top two quadrants). In contrast, the research developed in consultancy firms/design practices was more likely to be in the lower quadrants.

This distribution seemed to be coherent with the assumption we had.

Indeed, we read that—traditionally—the prototype is intended as part of a product development process typical of the industry. It supports the progress in making the solution real (concrete research). On the contrary, design research evolved towards more explorative, speculative, and experimental kinds of studies. We described this "academisation" phenomenon (see theoretical concepts in Sect. 1.2.4.1).

Nevertheless, we found exceptions to this simplistic dichotomy, as follows.

For instance, Case Study 3 is about the design consultancy Design Friction, "a design practice producing speculative and critical scenarios for the upcoming presents," as they claim. Thus, it is a design practice that develops purely speculative research. In this Case Study, the prototype supported the making of fictional experiences for the citizens involved in the project of future smart urban solutions. The firm's client was the city of Nantes. Thus, we had a squared icon in the speculative area of design research (Quadrant I).

Then, we have case studies made in the academic context in collaboration with industrial partners. In Case Study 5, the research team developed new concepts of smart bracelets for a fashion company. The research team made a first phase of the speculative research to explore possible scenarios and then set the final designs. In this case, the first group of prototypes supported the vision of alternative design opportunities, while the latter supported the progress toward concrete outcomes. So, maybe, this example well represents what a company seeks in academic collaboration. Indeed, Case Study 1 illustrates an example where the industrial partner entrusted the academic team with developing a whole vision for their future development in a specific area (health and safety). The aim of the research was fictional and explorative, even if it was for an industrial partner. The extensive making of different prototypes embodied that vision, both supporting the development of the design concepts and the communication to the partner. Indeed, we were told that the level of the partner's involvement in the future vision was crucial to the success of the collaboration. In this case, this reflection came from the sharing of data at the time of the interview. We should notice that the study successfully developed further later.

Yet, Case Study 6 represents the most unexpected example, a small design practice, DDP studio, that participated in a comprehensive study in collaboration with two large partners, the Italian Institute of Technology and INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro). In this case, the design team helped the engineers translate the user's needs (people needing prosthetic hands) into design requirements and solutions. They played an essential role in defending the value of form, an aesthetic feature usually overlooked in prosthetic design favoring functionality. Through making many prototypes, design and engineering aspects integrated into an innovative award-winner product.

Case Studies 4, 8, and 9 present the making and application of prototypes to develop advancements in design research.

Case Study 4 is an emblematic example of Research through Design (RtD). In this Doctoral thesis, the main research questions were about how designers used collections of visual material for inspiration and how new media tools could help the designer interact with such collections. The research was developed by making working prototypes and letting users experience them. The making of the prototype was essential to investigate the research questions.

Similarly, Case Study 8 is an example of RtD. Actually, the whole project is about prototyping. The prototype was used explicitly as a transition (from abstract to concrete) to make people understand the design concepts (social Internet of Things for cohousing Communities). The users' involvement was fundamental to gathering feedback and forming new knowledge about the future application of the new solutions embodied by the prototypes.

In Case Study 9, prototypes were realized to create new materials and show participants in the research workshop that they could make new materials by themselves. Even though the research is about something very tangible and made through physical prototypes, the research questions and findings are speculative as they regard the exploration of using cornstalk-based DIY materials to foster social innovation among Colombian small farmers.

So, this overview shows a manifold of cases that distribute and cover the quadrants in many possible crossing combinations. The exciting aspect is the variety of design research in which prototypes play a crucial role.

It was also interesting to notice the mix of applications, for instance, research of tangible things tested with digital and virtual prototypes and vice versa.

This case entailed two possibilities.

First, products might be embedded with digital technologies that need testing through specific interactive features of the prototype. For example, Heromix in Case Study 2 was developed with several models and prototypes: some simple physical models and some working prototypes that featured the interface interaction. Also, the product was presented to the client in a virtual environment. So, all kinds of "nature" of the prototypes were applied to this kind of industrial product (see Chap. 6 for further discussion).

Secondly, we collected under the name "prototypes" any item used during the research "to make the idea come true." Therefore, we included videos, scenarios, storyboards, and any other representation support that is mainly visual. If a case study included any such items in a digital version, it would appear in our results under the prototype's definition of the "digital nature." Nine case studies out of ten had digital prototypes of one of these types. This reading meant—we reckoned—that the use of any kind of digital support is commonly part of the design research process.

Lastly, we noticed that it also happened that intangible research objects, such as in Case Study 3 (a fictional experience) and Case Study 10 (an AI-based design tool), are developed with physical prototypes. These cases proved that the physicality of the prototype could be an excellent quality to reach the study's purpose. Either because the physical model could easily involve the stakeholders (Case Study 3); or because sometimes making simple paper prototypes is less time-consuming than making any digital ones.

Then, while all fictional prototypes appear in the speculative top quadrants, the virtual environment prototypes spread in all quadrants. Interestingly, they were all very close to the central vertical line (between tangible and intangible). We interpreted this distribution thinking that they let us experience the interaction, quality of the essence of the research that we would place between tangible and intangible (Fig. 3.4).

3.2.2 Reading Selected Relationships

We made the tool to visualise relationships. The first reading was of the still image altogether. Yet, the interesting extra connection could be seen by using the interactive selection that the tool supported.

As a first step, we checked the relationships between the Aims and the other information. We selected the Aims one by one and observed.

We discovered that most of the dots (16/27) belonged to the first three aims (Develop, Assess and Communicate). Thus, the prototypes made to "develop" and

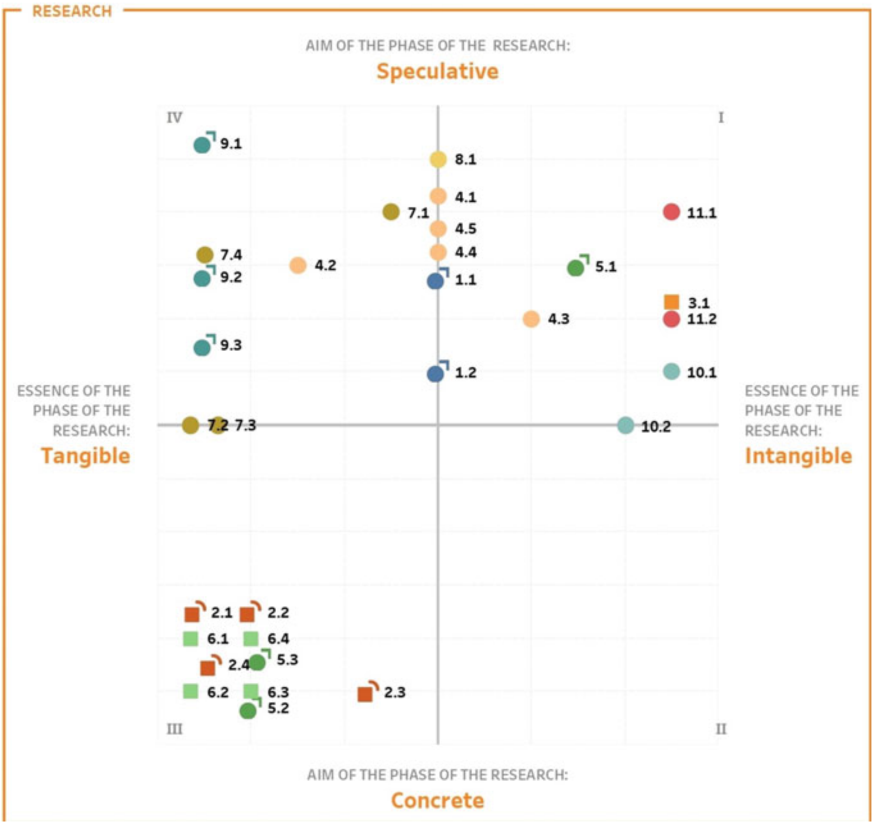

Fig. 3.4 Distribution of case studies in the research area of the interactive tool

"Communicate" are in different case studies, regardless of the research's context, aim, and essence.

While "Assess" appeared only in the upper quadrants. Possibly for these studies, the researchers wanted to highlight the presence of an evaluation phase that, apparently, is particularly relevant for such speculative studies.

At this point, it was vital to notice that the Aims "Comprehend" and "Provoke" were unrelated to any dot/case study.

So, while our literature review and Grounded Theory study revealed these two aims for the prototypes in design research, they appeared overlooked by the researchers during the making of the case studies. Remember that if it did not appear in the tool, it only means that none of these Case Studies had a phase/group of prototypes explicitly made for comprehending and provoking.

As regards the Aim of "Comprehend", we found out that one of the roles that prototypes play is to let the researcher understand the matter at hand, collect data and learn from the application of the prototype. Possibly in the researcher's interpretation, this Aim was enclosed with other Aims. For instance, when prototypes are used to Develop and Represent, many lessons are learned in the process.

Similarly, the Aim of "Provoke" could be associated with the Aims of "Investigate", "Explore", and "Envision" as they all support discussion and speculation.

Furthermore, the Aims Investigate and Envision appear only in Quadrants IV and I, confirming that such intents apply more likely to theoretical research. While Aim Explore is also in the III Quadrant, showing that experimentation through prototypes applies to speculative and concrete research.

3.2.3 Highlighting the Trends

After observing all possible relationships and reporting the most interesting ones, we wanted to highlight the sequence of dots belonging to each Case Study. It appeared that they could have sequential phases worth investigating. Therefore, after the interactive use of the tool, we connected the dots of each case study to show the trends, as in Fig. 3.5.

We observed that there is not one trend equal for all Case Studies. Indeed, three (n. 1, 9, 11) present a descending trend that shows a movement from speculation to concreteness, maintaining the same quality of essence (tangible/intangible). Case Studies 4 and 6 present a counter-clockwise circle of dots.

Case Study 4 represented a process where the prototypes supported a speculative start (4.1), towards development (4.2) and assess phases (4.3) where the project enters a more concrete realm, to end back into a reflective phase (4.4). The same progression happens in Case Study 6 but all in Quadrant III since the research was *concrete* in all phases.

In Quadrant III, Case Study 2 presents a clockwise circle of dots. The dots following the first one, move on the quadrant and come back to the starting alignment to the vertical line while they descend in the horizontal line. It seemed that these prototypes helped diverge from the starting questions and reached more concreteness.

Also, Case Studies 5 and 7 move down towards concreteness and from right to left toward more tangibility, but both come back up for reflection in different quadrants.

Only Case Studies 3 and 8 have only one dot, meaning that all prototypes used in these studies share the same main aim (Fig. 3.5).

3.3 Discussion

The tool appears to be useful for reflection on one's research, as we discussed in our team, and to debate with other researchers. Overall, we noticed some themes emerging from using the interactive tool.

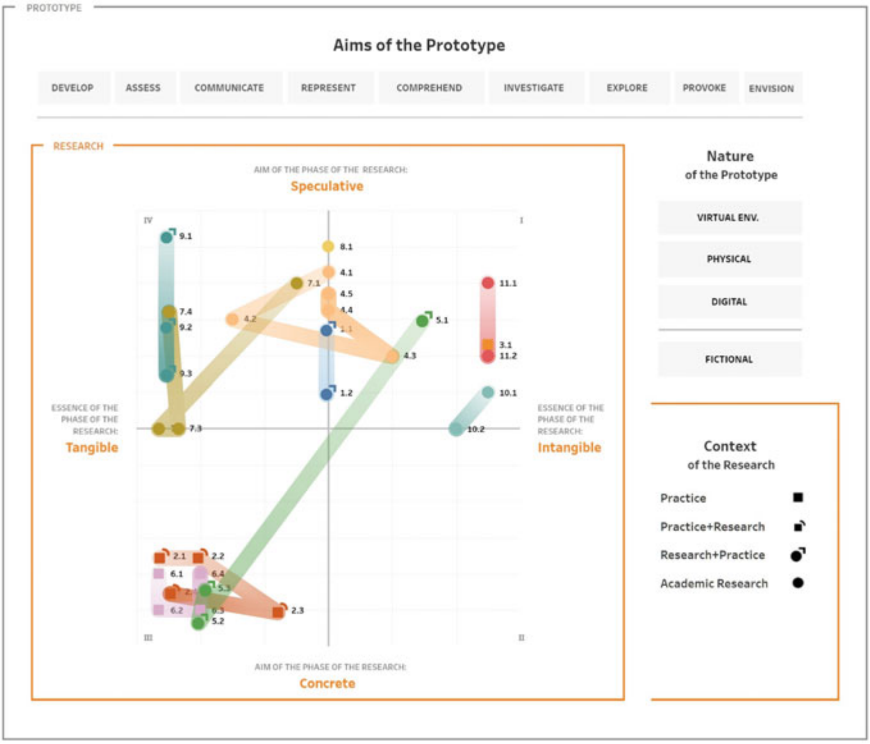

Fig. 3.5 Trends of research phases using different prototypes for specific aims

3.3.1 About the Phases and Trends of the Research

We realized that different prototypes are developed for different aims in progressing phases of the research. These trends could go toward concreteness or speculation and move from more tangible or intangible parts of the research's object. There was no common trend or strict analogies of similar Case Studies, even though most of them presented a descending movement, which confirms that the prototypes role is to make ideas more concrete. The ascending final dots (those in an upper position at the end of the trend) aim to represent the final design or extend and assess the research both towards theoretical findings or actual development.

While we observed the trends, we realized that the groups of prototypes did not represent all the phases of one research. Thus, a preliminary part of research without a prototype (i.e., a benchmark or state-of-the-art) would not appear in the visualization. Similarly, a final theoretical reflection phase, with no prototype, was not present in the tool.

So, it was essential to highlight that the role of prototypes in design research might also be relative to just a part of it, not to the whole study.

We also realised that, while in an industrial production process the development phases are quite standard, there was not such a consolidated reference in design research. Thus, the definition of phases is entirely relative to each investigation.

Discussing the findings, we also realized that it was essential to consider the research level of development. Some of the Case Studies were about research that developed further or became part of larger studies. So, the role prototypes might play in the first research might continue and evolve later, in other studies. For instance, Case Study 5 became part of a doctoral thesis, and thus, in that context, it contributed to developing a speculation phase that is not pointed out here.

Similarly, for the Case Studies that do not end with a reflective phase, we thought that it could also mean that the theoretical knowledge did not develop together with the ongoing research but might have followed later or been developed by others. In Case Study 6, the designers did not dedicate time to generate theoretical knowledge from their results or formalize them into publications. In contrast, the engineers researching with them elaborated and shared their findings from their point of view.

3.3.2 About the Overview

After making and using the interactive tool, we realized that we expected to collect examples of case studies conducted with a "Research through Design" approach and conducted in academic contexts to fall into the top quadrants (the "speculative" area of the scheme), and that was confirmed (see Case Studies 4 and 8). Also, we expected to collect examples of case studies conducted with a "Research for Design" approach in practice-based contexts to be in the bottom part (the "concrete" part of the scheme). And that is confirmed by Case Studies 2 and 6.

However, what was interesting to observe the exceptions. Case Study 3 was made by a design consultancy for a town council with a design fiction approach (top quadrant). Case Study 5 was a study made in an academy for an industrial partner that crosses from top to bottom quadrants. Case Study 1 was made in an academic context for an extra-academic industrial partner, but it pertains to the speculative area, possibly because of its fictional approach. Case Study 10, the study of this book, is a "research about design" and falls into the top quadrant. It is interesting that even such a theoretical work was developed through making a tool that required prototypes that definitely contributed to our *understanding* of the issue and to the development of the final reading.

Eventually, we can say that the role of prototypes in design research varies according to the context in which the study takes place and the general aim and object of the research.

One research might require prototypes of different natures (physical, digital, etc.) that are developed to achieve specific aims (develop, assess, communicate, etc.) in a different investigation phase. Even if research in the academy is more commonly speculative and research in a practice-based context is concrete, nowadays, design may cross such boundaries, as speculative and fictional approaches are helpful also for practice-oriented (concrete) research.

To conclude, we reviewed the literature and analysed it with two approaches. We applied the Grounded Theory Methodology to develop a general understanding of the phenomenon. This approach defined four theoretical concepts that gave us a comprehensive knowledge base to build our research. In the meantime, we gathered and organised information based on some categorization criteria that let define the prototypes. These results gave us a reference framework that we used to develop our study further.

Indeed we mixed these results to make an interactive tool that could visualise the essential relationships that define the prototypes and the studies they are made for. Then. We interviewed experts and collected Case Studies. We placed the case studies in the interactive tool to confirm or discover relationships that frame the role of prototypes in design research.

In this chapter and Chaps. 4, and 5, we report the Case Studies and the discussion raised during the interviews. Further insights developed from the deep investigation.

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Chapter 4
Prototypes for Speculative Design Research

Manuela Celi, Valentina Rognoli, and Camilo Ayala-Garcia

Abstract The activity of speculating through artefacts (from the more material and tangible to the more immaterial and intangible), produces fictional worlds and opens up possibilities. Prototyping is a way to explore the borders of the possible, questioning different forms of materialization that are not meant to reproduce or reshape products but to explore scenarios embedded in materials, actions, performance, and possible futures. The aim of a prototype is not to predict the future but engaging with possible future solutions addressing the preferable one with a critical perspective. As authors of this chapter, we selected two cases in which prototypes are considered tools for dialogue and reasoning along the development process. For the first case, we interviewed Bastien Kerspern, Co-Founder of Design Friction, Nantes, France, who shared a research project called "The Rules for the Game for the Smart Streets". They organized workshops involving citizens to collectively define a set of recommendations regulating the experiments of new technologies and new uses taking place in the public space on Nantes Island. In the second case, we shared the research "CornStalk DIY-Material for Social Innovation", where using cornstalk-based DIY materials to foster social innovation among Colombian small farmers.

4.1 Prototypes in Speculative-Intangible/Tangible Design Research

The activity of speculating through artefacts—from the more material and tangible to the more immaterial and intangible—produces fictional worlds and opens up possibilities (Wakkary et al. 2015). In general, any prototype has the opportunity to propose alternative futures, thanks to their characteristics to favour and facilitate speculation. Building projects through iterations of prototypes—or provotypes—are

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PoliMI SpringerBriefs, https://doi.org/10.1007/978-3-031-24549-7_4

both means to critically reflect on possible solutions and a way to problematize an issue. They are the materialization of future scenarios that inquire and create tangible points of interaction and co-generation. Prototyping is a way to explore the borders of the possible, questioning different forms of materialization that are not meant to reproduce or reshape products but to explore scenarios embedded in materials, actions, performance, and possible futures. The aim of a prototype is not to predict the future but engaging with possible future solutions addressing the preferable one with a critical perspective.

The prototype characteristics and level of definition are not pretending to be high-fidelity, but they aim to simulate hypotheses that are still blurred and undetermined. In both cases, prototypes have an experimental dimension and are not generated for market purposes in the short term. They are a way of materializing the possibility between tangible and intangible matters.

Both presented cases present similarities and differences. When the act of prototyping occurs while experimenting with materials, the different iterations are connected to tangibility and manipulation and for sure concerns concreteness and physicality. Experimental activities, in this case, are seen as knowledge through practice based on sensorial interaction, followed by active reflection (Nimkulrat and Groth 2022; Parisi et al. 2017).

In the Design Frictions case, the tangible element is a draft that can also be digital but which, in reality, is, in any case, fictitious, fictional and absolute and far from its real and material dimension but which still helps to simulate a possible situation. In these cases, prototypes are often linked to intangible issues because they are related to service.

As a testing *transition*, we stated in Sect. 2.3.4 that: "prototypes in the field of design serve the fundamental need to make magmatic and conceptually embryonic ideas manifest through fathomable forms of representation. Although the whole field of design research intends and employs prototypes as means to make ideas manifest, moving from vagueness to clearness, the way such representation is understood and achieved varies depending on the research areas, to the point of generating opposite poles: speculative and intangible on the one hand, material and realistic on the other. Such a dialectic tension, to conclude, shows how physicality is no longer a fundamental requisite for the prototype to be deemed such. In this respect, prototypes can be intangible and imaginative as long as they give prototypical form to the developed design ideas."

Through future scenarios and by elaborating on speculative prototypes, we can visualize tangible futures that allow us to gain insights into users' mental models and expectations for the future.

One of the aims of speculative experimentation through prototypes is connected with the relationship between speculative design and ethics: the two cases presented in this chapter—from different perspectives—engaged with speculative methods and reflect through design research not only to explore new solutions but to raise awareness of design's agency.

As design scholars, we believe there is a pedagogical interest in raising awareness and constructing a more critical approach to new product/material developments beyond the micro-environment of specific design disciplines or industrial contexts.

Moreover, the experiences explained hereafter would frame how speculative prototypes can be performed through different shades of materiality to make the future visible and the opportunity to involve communities and reach a social aim through design.

4.1.1 *Speculative Intangible Prototypes: Provotypes for the Design of Possible Futures*

The most accepted connotation of the essence and role of the prototype in the design process consider prototyping as the ability to translate an abstract concept into a tangible object, to draft the first version of a blurred idea, or unveil its nature through an initial representation. As already stated, prototypes are intrinsically connected with the capacity to project the future, but in a speculative context. When dealing with groundbreaking ideas or in a far future hypothesis, prototyping is not a way to shape or refine the design; it's a way to simplify a very complex scenario. In this context, we can talk of "provotypes". In the early nineties, Mogensen (1992), describing the particular condition of systems design, introduced the idea of provotype as a tool to visualize norms and create a space for conversation about norms, design, and desired futures (Boer 2011; Ehrnberger 2017). The provotype can then have a double aim—to be used externally (i.e., outside the research project) to explore and encourage dialogue and to be used internally as a tool to create norm-conscious spaces. What can be interpreted from earlier research is that there is no specific way of using a provotype but several different approaches.

4.1.1.1 Design Fiction Approach with a Critical Political Twist

Design operates pragmatically and imaginatively toward the future (Yelavich and Adams 2014) with the acts of making and anticipation to create products, services, and interactions above the strategies and systems of the here and now. However, connections and distinctions between design and future studies are under-articulated (Celi 2017), and there is a specific research space that opens several different perspectives to deepen the topic: Design Fiction. James Allen Dator—a pioneer in this academic field—has spent the last five decades pondering what the future might grasp and affirms that: "Futures studies does not—or should not—pretend to predict 'the future'. It studies ideas about the future—what I usually call 'images of the future'—which each individual (and group) has (often holding several conflicting images at one time)" (Dator 2019). The contribution of design to combine the anticipatory practice with design passes through the *materialization* of new and more inventive possibilities. It provides new and lateral learning through prototyping and experiencing alternative futures (Candy 2010).

The field that has best embodied this approach in recent years is represented by what is known as "design fiction". Design fiction is a provocative term. It presents a cluster of problems rather than its naming issue. Design fiction—a term born from the pen of the visionary. Bruce Sterling—is those contemporary practices of forward-thinking intervention. Described as "the deliberate use of diegetic prototypes to suspend disbelief about change", Design fiction can be considered as both a means of representing and a means of intervening.

Design Friction is a design studio based in Nantes and Paris (France) investigating emerging issues in social, cultural, and technological changes that challenge our societies. The name of the studio itself tells a lot about its attitude: it's a tribute to PopupUrbain and the notion the coined of Design Friction as:

> Prospective method consisting in exploring deliberately corrosive and non-pragmatic scenarios and imaginations in order to stimulate creativity. Similar to design-fiction, of which it is the caustic cousin. (Gargove 2013)

The Design Friction approach develops speculative scenarios and arranges imaginary spaces, objects and services, offering a different perspective for discussing expectations for the evolution of organizations. Projects from the studio often address complex controversies to the public who are not aware of them and are designed to be open and participatory. Design Frictions studio's main ability and particularity rely on embedding questions in fictional products to nurture critical thinking on trends that will shape our futures. They work with public and private organizations and use provocative and reflexive scenarios to activate debates with stakeholders and produce decision-making tools to face uncertainty and complexity. Moreover, they often produce self-commissioned research to activate a virtuous reflexive process with pure speculative and mission-driven research.

We interviewed Bastien Kerspern, cofounder of Design Friction, about our theoretical concepts. When discussing Concept 1, "Transition" (Sect. 2.2.4.1), he said that overall, he agreed with our definition, which—he noted—could also apply to digital design, service design and interaction design. But he added that in the case of speculative design and design fiction, he would maybe be a bit more of a disagreeing position. Indeed, he said that in these practices, prototyping is not a way to refine the design; it's a way to simplify very complex scenarios. In the case of Design Fiction/Speculative Design, he thought there was an interesting duality in the term "representation" attached to the prototype.

We discussed and agreed that visualization is fundamental in design practice. According to the stage of the process, designers produce visualization with different motivations: communicating insights, shaping them and, facilitating concept comprehension, maintaining empathy with the stakeholders for including visualizations in their practice. In a study of service designers (Segelström et al. 2009), three theories were identified when the service designers captured raw data visually. The first was to maintain empathy with the stakeholder; the second was to communicate insights, and the third was to articulate insights. The visualizations used to maintain empathy with stakeholders ensure that the users' input is not forgotten in the research process. Not maintaining communication with the user may lead to the creation of a self-centred rather than a user-centred design (Pruitt and Aldin 2006 in Segelström et al. 2009).

> Futurists must rethink scenarios as a process and a tool and discover ways to use them much more effectively as powerful stories that can motivate reshaping the future. (Jarratt and Mahaffie 2009)

Narratives are the main device through which people can re-frame realities and get engaged with different stakeholders in an active change. Jarratt and Mahaffie (2009) argue that we don't need a better rational argument for the benefits of thinking about the future. Still, we need better stories: brief sketches and short stories represent the unit of information through which we codify, comprehend, and learn in our life. Gizmo, props, or provotypes are a first idea presentation that can be experiential and tangible; in Design Friction projects—for instance, with prototypes of interface—it's not tangible, you can't play with a mockup, sometimes is very it's very aesthetic. The use of visual notes, sketches, and images plays a crucial role in the generation of creative thinking by designers. Smith et al. (1995), analyzing the approach of different authors to creative thinking, also evaluate that many studies converge on the fact that non-verbal processing, including visualization, often improves creative intuition. Visualization can be considered a form of pre-invention, as Finke (1990) embodies in his study of creative realism through research on creative visualization.

When we asked if he would place his research activity in the realm of "material and realistic" or "speculative and intangible" or across, he said that most of our prototypes are materialistic and realistic and that the goal of presenting is speculative and tangible. He added that most of their prototypes are *materialistic* and *realistic* and that the purpose of presenting is *speculative*. Prototyping-wise, he continued, it could be both depending on the context; when they do more storytelling-based prototypes, sometimes it's very speculative and intangible because it's a prediction of a situation we are creating; people are making the choices. Playing games, for example, it's very speculative and intangible. Still, for example, the game is a material prototype and realistic because the prototype uses actual resources and, like a videogame, also embeds many hours of work from different people, so it is material in a way. He added that it would depend on the context, and he is more interested in combining material and speculative realistic intangible. Thus, he concluded that they work across them. Indeed, in the very specific practice of design fiction, it is a mediation of the questions of the future; it's somehow a mediation of the actual and current state.

The studio focuses more on problem framing and finding rather than problem-solving, even when using the codes of methods of design prototyping, with the same postures or the same goal. Design friction adopted the use of the term 'provo-types'—like provocative prototypes—implying a distinction between the classic design prototypes that are supposed to validate an idea and prototypes that are here to create dissensus rather than consensus.

We discuss how stories should captivate the audience and get them to act on long-term goals, make them feel empathetic, and then motivate them to stick to the scenario. The scenario is much more effective when storytelling has the power to break stereotypes (Celi 2017). With speculative provotypes, if we raise questions and provide all the answers, we are not doing an excellent prototyping job regarding this design fiction criteria. Kerspern considered that one of the significant learnings in prototyping is that we don't have to do a good fiction with all the answers; we don't pursue the classic design job of anticipating everything; with a different attitude, we have to let it go with a prototype so people could do part of the job for you filling the gaps. These gaps are the activator of people's participation: incompleteness allows people to project themselves in the future, leaving enough space to explore the prototype and re-frame it in reality. It's a very different way of envisaging a classic prototype for a different application and scenario to think about the future: an imprecise rough provotype that opens possibilities. This kind of prototype has shown that engaging the provotypes through interactive fiction facilitated complex and productive interactions and critiques (To et al. 2022).

When asked about Concept 2, "Making theory", in particular, our statement that "Besides the traditional testing, validation and verification of production requirements, the prototype has taken on the role of means for reflecting on the design process", Kerspern agreed that it is true especially in the case of speculative design, when you are trying to address a theory of what could be the role for prototyping. But he added that when designers prototype in a Design Studio or Integrated Design team, they are not really reflecting and what they are prototyping; they start to test an idea but not really looking at whether prototyping is providing a vision of the world which is something that is not even conscious, it's not on purpose. Furthermore, he agreed with our second statement: "making theory through prototyping is the most significant aspect of a new way of intending the role of prototype in the field of design research, whether the latter is purely academic or practice-oriented". Especially in the case of design fiction and the speculative, he said that a prototype could be used to challenge the current status, but with classical design prototypes (such as for interaction/service design), it might reinforce the dominant theory or status quo. However, he completely agreed with the fact that it's a new role for prototyping in the field of design. That is a different way that the prototype can be used.

When asked about Concept 3, "Evolution", Kerspern said that he completely agreed that interactive prototypes for design fiction provide different levels of use and reading of the context. He also reflected on the fact that the prototype has always been shifting, and at some point, it was a *perfect* product, and now is more of a drat object thanks to the technological digital revolution. Also, he said this trend has an impact on the way we waste prototypes because it's easy to produce and replicate them; in order to test, we tend to *sacrifice* some ideas in a quicker way; these consequences impact the ecological, socio and environmental aspects that are not always considered enough.

When asked about Concept 4, "Milieu", Kerspern agreed with the idea that the context influences the research activity. He also pointed out the importance of awareness of the context when we are doing prototypes and research. We are aware of everything that is influencing the way we are prototyping or researching, he thought that it's true for many research disciplines such as humanities. Yet in design research, still a young discipline, sometimes we use ideologies we are adopting and especially in design practice, we do not question why we are doing prototyping because we are being told to do it in school, but you don't really question the influence of prototype on the context or on the user's context. He added that it's really different in the design fiction context because we're working with fictional prototypes, and they're a different vision of the story, the world, or the future. There is a debate in the design fiction community to know if we should signal the fictionality of the prototype because the context can influence the research activity based on the design fiction prototype. The design fiction prototype can also completely shape the context because of its fictionality, and it introduces a form of fiction in the reality.

To conclude, Kerspern did not agree with our reading of the phenomenon that we called "academisation". Quite the contrary, he said he would see "practicalization" and professionalization of the designed research discipline rather than the academization of the design practice. He used "Design Thinking", which first started as an academic concept that was so much used by IDEO and the other design agencies, and now we're seeing that academia and even design research extend to go on this way of thinking. He added that could be because of the economic perspective since everything is economically driven in the design market. I regretted noting that in schools and universities abiding by the market narrative or what design should be, there is this "Marketisation" of the design research rather than the Academization of the design practice.

4.1.1.2 Case Study "The Rules of the Game for the Smart Streets"

The selected case study by Design Friction studio, named The Rules for the Game for the Smart Streets, took place from September to December 2018 in Nantes Island, France, a scene of projects and experiments that link public space and data (Casus Ludi n.d.). The project was co-led with diverse partners; Creative Factory, "a division from the urban planning and development bureau for the Atlantic West Metropolitan area in Nantes, France" (Design Friction n.d.); and Chronos group, a foresight social research agency. These were joined by the studio Casus Ludi, the creators of the workshop methodology used; and the Société d'Aménagement de la Métropole Ouest Atlantique (Samoa).

The Rules for the Game for the Smart Streets outlined "the use of personal data for new public services" (Design Friction n.d.) using prototypes through a participatory approach. The objective was to gain citizens' trust by constructing a framework for these connected street experiments (Casus Ludi n.d.). The aim was to develop recommendations that would regulate the insertion of new technologies in the public space, as defining the game's rules. These guidelines were defined collectively, involving local representatives leading the project and stakeholders that made the final decisions. These actors ranged from people belonging to the municipality, who helped build and set up the project's framework, and a very heterogeneous group of citizens as central participators, addressing the process as a democratic experience, putting together people with different digital literacy dexterity, age, and gender.

Fig. 4.1 Collective frequently asked questions session to identify the definitions of a connected street (Billaud and Samoa 2018)

The project was held in three different workshops; the first aimed at understanding and imagining what experiments use digital data (Fig. 4.1). The second workshop built a draft set of requirements respecting the participant's shared values. The last workshop, led by Design Friction, crash-tested these initial recommendations given by the participants; this testing methodology facilitated a speedy trial in which the unthought implications of these proposed rules were brought to light, defining their follow-up modalities and evaluation (Casus Ludi n.d.).

The Design Friction studio put into practice the use of prototypes to enable the futureproofing of these imagined rules, making the participants envision the possible impacts they may have, anticipating undesirable outcomes, and understanding these rules' relevance and resiliency along a set time frame (Fig. 4.2). Participants were encouraged to imagine themselves as masters of the game, defining the powers and duties of each of the actors (Casus Ludi n.d.). Several prototypes were developed as both highly and hardly faithful. This wide range gives the prototypes enough flexibility to carry out the research in an open way, allowing the project to pick up valuable issues, translating them from abstract to concrete, identifying problems, and producing new knowledge.

To do so, the studio created four different design fictions that allowed the experimentation of these proposed rules, bringing four scenarios that extrapolated the regulations first drafted by the local participants (Design Friction n.d.). This way, with the aid of prototypes, citizens could explore and experience first-hand the extent of the envisioned reality, understanding what can and cannot be done. After implementing the proposed regulations, these scenarios were set on a 5-year future projection, allowing their respective design fictions to question possible and unexpected consequences critically (Fig. 4.3).

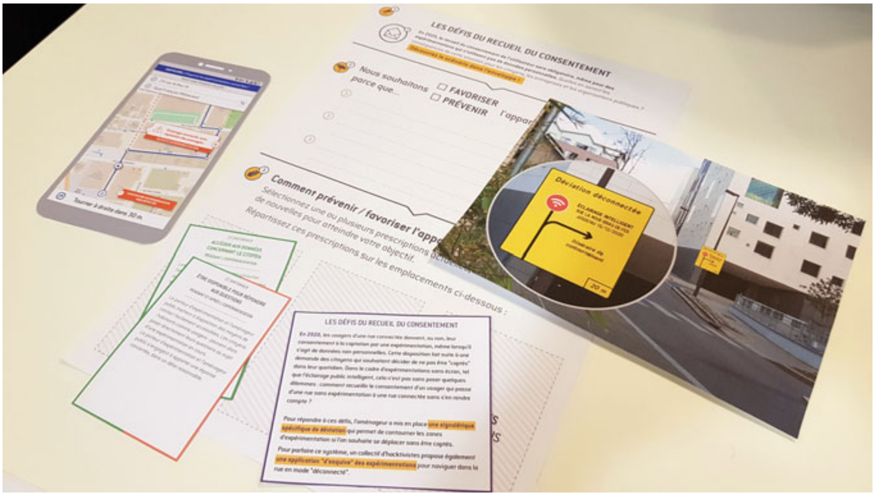

Fig. 4.2 Design fictions to anticipate the applications and implications of imagined prescriptions (Casus Ludi and Design Friction 2018)

Fig. 4.3 Design fiction photomontage for the workshop (Design Friction 2018)

The envisioning of these four prospective situations resulted in an open debate among citizens. The discussion revolved around the preferability of the outcomes, revisioning the proposed set of rules to prevent the less desirable outcomes while fostering the most desirable ones (Design Friction n.d.). In this case, prototypes played an important role not only in the assessment stage, acting upon the evaluation, analysis, and improvement of the resulting ideas but also in facilitating the comprehension of the topic, enabling a space for sharing and negotiating between participants and stakeholders.

Together with prototyping and participatory approaches, the studio introduced the concept of ambiguity, presenting it as given specific situations in which the participants gained a glimpse of multi-fold futures. As the prototypes used at this stage were very open, they encouraged a free projection of the ambiguity of the situations presented and promoted an unbounded conversation that discussed what rules to apply to limit or stimulate the development of these situations.

One of the ambiguities implied the challenge of obtaining citizens' consent to process their data when walking around the neighborhood. Suppose someone were to pass by a connected street with intelligent lighting devices that lit up when standing nearby. Should one be asked for their consent to be detected by these smart object's sensors, although one's identity would still be anonymous? If so, how would the following procedure be? Should one fill in a form or use a smartphone application to give this consent? Other questions raised referred to other ambiguities, such as: dealing with the spread and boundless use of artificial intelligence in urban infrastructure; or the "public audit of algorithms used in connected urban solutions" (Design Friction n.d.).

This case study also exposes how prototypes may be used as an immaterial context activator, portraying themselves as a powerful tool for thought-provoking and decision-making (Fig. 4.4). Take the example of the hacktivist application prototyped for this project, an app used to avoid the connected streets together with the official signalling pointing out what street is connected, allowing one to choose whether to take that route.

The Design Friction studio created prototypes for every ambiguity case suggested. These were to support or oppose the given case, designing various prototypes that expressed a polyphony of visions for the same situation. Having multiple prototypes that showed diverse points of view was crucial to reduce the influence on the participant's perception of possible futures, keeping it as unbiased as possible.

In this case, prototypes enabled a reflection upon these ambiguities in a more direct way, being able to showcase and gather feedback more efficiently. Their role of simulating, visualizing, and embodying was crucial given that the participants were not designers or experts in the subject, allowing them to project themselves and understand their positioning regarding the given issues. Prototypes facilitate the conversation by questioning how they would like these situations to unfold and what possible impacts they may have in the near future. Once this last stage crash-test workshop finished, studio Casus Ludi and Chronos group synthesized the results taking them from fiction to action. These results were delivered as recommendations about how to inform the public, audit the algorithms used, share the resulting data

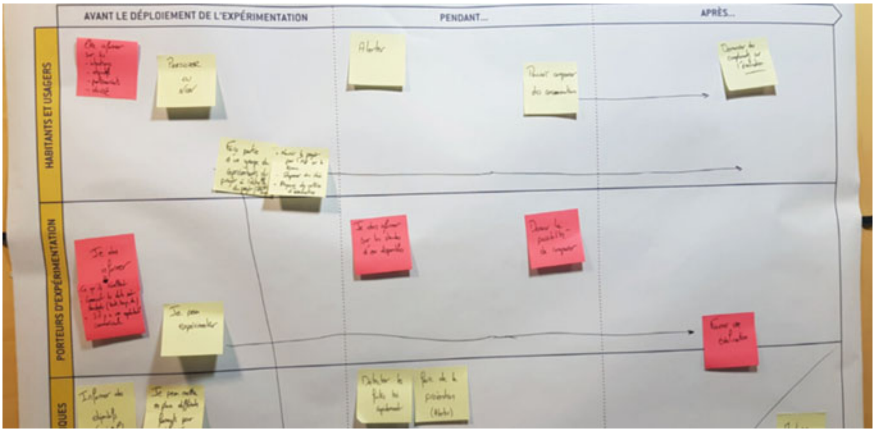

Fig. 4.4 A role-playing game to set out the opportunities and obligations of the actors of the connected street (Casus Ludi and Design Friction 2019)

from the experiments and evaluate the systems (Casus Ludi n.d.). This translation from fiction to action evidence how this approach may enable a collaborative innovation process by applying a methodology that provokes a critical discussion and evaluation (Design Friction n.d.), understanding prototypes as a vehicle of social construction.

When analyzing the prototypes according to our framework, we realized that all the prototypes of the research were made with the specific aim of "envisioning". Hence, we grouped them in one spot of our interactive tool. The research is placed in the I Quadrant, where it is studied with a speculative purpose, and the essence is intangible (Fig. 4.5). It is worth reminding that we selected the quality "intangible" being the Case Study addressed, making a fictional scenario for a city service. However, some parts of the prototype could have tangible features. Most of all, it was interesting for us to notice that the top quadrants are not just doctoral theses, meaning that speculation in design has reached design practice.

4.1.2 DIY-Materials Drafts and Demonstrators as Speculative Tangible Prototypes

In many areas of design, not only in product design, materials are today the protagonists of the creative process. Over the past twenty years, research on design materials has shifted from the engineering approach of molecular understanding of behavior to a physical interaction with materiality, a common practice in the design domain. It is possible to refer to a "designerly way of knowing and considering materials" (Cross 1982) in the design process.

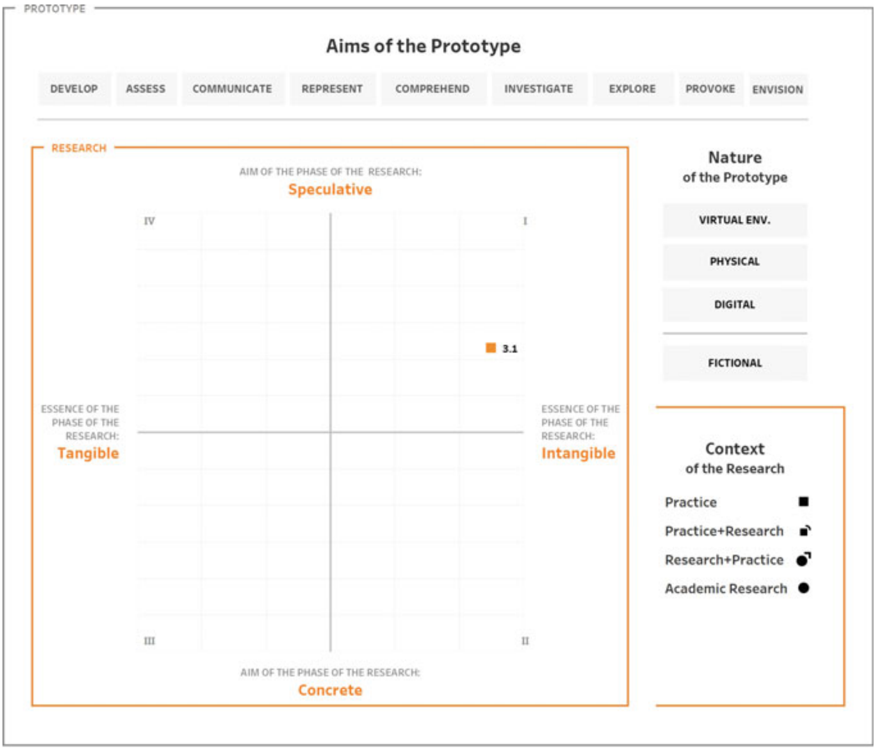

Fig. 4.5 Case Study "The Rules of the Game for the Smart Streets" displayed in the interaction tool

The "designerly way" perspective enables experimental research and allows the development of physical and speculative prototypes around which to think about design materials.

The prototypes of design materials provide and facilitate the material experience.

The materials experience concept (Karana et al. 2014; Pedgley et al. 2021a) consists of four experiential levels: aesthetic or sensorial experience (e.g., we find materials cold, smooth, and shiny), the experience of meaning (e.g., we think materials are modern, sexy, and cozy), emotional experience (e.g., materials make us feel amazed, surprised, and bored), and the performative level which involves novel actions and, ultimately, practices of interacting with materials (Giaccardi and Karana 2015). Accordingly, this four-level framework underlines the active role of materials not only in shaping humans' dialogues with artefacts and our ways of doing (Pedgley et al. 2021b). The four-level framework expanded the territories of Materials and Design, including a critical perspective on the changing role of design/designers, the improved prevalence of Material-Driven Design (MDD) practices (Karana et al. 2015), and the increasing attention among design scholars to the role of materials themselves as active and influential agents within and outside design processes.

Thanks to the materials experience lens, we observed the broad and vibrant world of design materials and the incredible designers' willingness and abilities to self-produce their own materials instead of choosing them from an already prepared library. This active phenomenon of making materials instead of selecting materials for the project was called DIY-Materials (Rognoli et al. 2015).

In recent years the DIY-Materials phenomenon has expanded enormously, requiring more refined ways of describing the material-making processes and organizing the already created materials. DIY-Materials are defined by sources of substance that may be uncovered in one of five material kingdoms (Rognoli and Ayala-Garcia 2021; Ayala-Garcia et al. 2017). The active role that the DIY-Materials approach presents to the field of design has to deal directly with the possibilities to imagine, create and deliver material concepts through direct experimentation. Similar to what happens when designers prototype ideas of artifacts in an iterative way, designers who are engaged in DIY-Material practices explore different sources, test recipes and iterate various alternatives of material concepts to find the better ones.

Experimenting with unconventional sources involves developing materials through an iterative act of prototyping. Thanks to practices promoting a form of "knowing in action" (Schön 1984), it is possible to get some experiential knowledge with and through materials. In the earliest phases of development, the designer typically experiments with low-tech tools and equipment, often conceiving and producing these tools directly. Such experimentation is essential to learning material possibilities and is called "tinkering" (Rognoli and Parisi 2020). In this case, the tinkering activity leads to two types of prototypes: drafts and demonstrators.

Designers start tinkering with materials from the most disparate sources, producing material drafts equivalent to low-resolution prototypes. "Tinkering with materials" aims to obtain information and understand their qualities and empirical properties, recognizing constraints and identifying potential. It means working with the hands and the direct involvement of all human senses.

Material demonstrators are the results of the "tinkering for materials" activity. These demonstrators are an iterative evolution of the material tinkering process, which in turn become a kind of high-resolution prototype of materials. Tinkering for materials requires a declared intention by the material designer to investigate further. The promising material drafts evolve into demonstrators; material designers already have in mind an idea or a vision they want to verify in terms of materials and process innovation. These demonstrators aim to make the superficial and formal qualities of the hypothetical material perceptible and concrete. This kind of prototyping activity is fast and does not require significant investments, sophisticated tools or processes. However, they are also beneficial for undertaking speculation and critical design actions, pushing the material designer to create scenarios and visions and envision future applications.

Scholars (Barati et al. 2016; Parisi et al. 2017) argue that material demonstrators help frame and communicate material knowledge among material experts, designers and users. Tinkering with materials can therefore be considered an "Experience prototyping" activity (Buchenau and Suri 2000), which allows for a first-hand appreciation of existing or future conditions through active involvement with prototypes. This approach facilitates various activities during the design process, including understanding, exploiting, and communicating the experiential aspects of design and predicting the use of the future artifact through iterative exploration. It is perfectly consistent with the fact that prototypes are defined as media—places and platforms for collaborative creativity [...] they are means for interpersonal—not just technical ends. In this perspective, prototypes are not defined by their features but by their purpose (Schrage 2013).

Material drafts and demonstrators are valuable for their purposes (what they're made for) rather than other qualities, such as their fidelity (how much the prototype looks and acts like a finished product). Indeed, these let designers formulate hypotheses, promote understanding and discussion on the value of design, and allow a relaxed approach to ideas exploration and speculation. Hence, speculation through DIY-Materials can lead to engaging communities and achieving a social purpose through design. This happens when communities can observe the process of material experimentation and engage in a similar phase of experimentation. Additionally, speculative DIY-Materials help build alternative futures that are rarely conceived through classic approaches of materials development.

The concept of material speculation draws on the literary theory of possible worlds, which demonstrates that, like fiction, design can generate alternative possibilities or possible worlds that critically reflect on our own world. This type of prototyping approach intends not to develop a proper material solution for a state-of-the-art application in the specific case of materials. It is to generate a draft or a demonstrator which proposes a vision of possible parallel worlds where these materials can be applied and transformed into artifacts of other languages, far from what we are used to seeing in the actual status quo of our society.

Materials, in general, are conceived in classical engineering terms and should be developed with a precise application in mind. Material drafts and demonstrators suggest possible applications that were not imagined before.

DIY-Materials, as mentioned above, is an emerging field that has progressively gained attention because of its democratizing power and business potential. In this Case Study, we aim to present how the iterative process of prototyping through material drafts and demonstrators using cornstalk-based DIY-Materials helps foster social innovation among Colombian small farmers. As a speculative approach, it promoted a rural development that respects farmers' traditional practices and beliefs oriented towards collective progress and nature preservation. This is rarely possible by conventional ways of development posed by political programs or government decisions, which believe that only through the industrialization of agriculture farmers prosper economically. Hence, the theoretical review regarding social innovation, circular economy, DIY practices, and materials is tested by proving that corn stalks can be used as a raw source to make materials without the need for scientific knowledge, sophisticated technology, and polluting processes.

The selection of this Case Study started with an interview with Camilo Ayala-García, who then participated in writing it. We asked for his feedback regarding the four theoretical concepts defined in our framework.

When asked about Concept 1, "Transition", he agreed that prototyping is at the very essence of the design discipline. Indeed, he said that evolving ideas into projects through prototyping always produces tremendous results. Doing and testing rough ideas starting with low-res prototypes to improve and refining with Hi-res prototypes, leads to better design outcomes. Regarding the tangible feature of such *transition*, he added that a prototype aims to translate thoughts and insights into something probably not "tangible" but visible. There are many ways to produce a prototype and different media to achieve it. The term tangible is tricky. If tangible refers to the capacity to grasp the prototype, we would be denying the possibility of using multiple media sources to test the project's components. On the other side, if tangible, it may refer to something represented by different media sources and is a brain-hand connection where ideas are produced. Then it may be the correct term to use.

When asked about Concept 2, "Making theory", Ayala-García agreed that in design, unlike other more technical disciplines, the prototype is a mean to approach not only the possible shapes or characteristics of an artifact. It is a mean to reach a user or a community. In that sense is an element for building theory. For example, in places where communities are disconnected from the traditional urban settlements (i.e., Indigenous communities), we use low-res prototypes to approach the community and even to co-create with them. Such elements become means to produce theories and interact with other disciplines, such as anthropology or sociology, which cannot imagine the capabilities such prototypes enable in the place of study. Designing without prototyping doesn't make any sense. As design is a discipline that has evolved from the "making of things" to the "imagining a better world", it is mandatory to use prototyping as a tool. Not a tool to refine ideas but a mean to construct ideas. It is, in my opinion, one of the "secret tools" of the discipline. When working with other more classical or traditional disciplines, one may always encounter that they tend to rely on other sources to conceptualize or pose problems in the early stages of the projects. In our case, we go directly to build prototypes, unlock different insights or tackle problems with surprising speed.

When asked about Concept 3, "Evolution", Ayala-García commented about the iterative process of prototyping being now more successful and time-efficient. He said that product design and engineering is not only the only arena where this approach is happening. The user experience is not only measurable through iterative prototyping for interactive products. Services, bio-design, or policymaking as well. The gathering of other disciplines into this way to operate and iterate merges the fields of knowledge and their methodologies.

When asked about Concept 4, "Milieu", Ayala-García told us that when he was teaching at the Universidad de Los Andes, the vice-rectory of research had recently changed its name to vice-rectory of research and creation (Vicerrectoria de investigación y creación). This shift happened as the different disciplines that compose the university have recently realized the capabilities we are posing when developing research from a design perspective. The university funds multidisciplinary projects inside, and we can work on different projects with lawyers, biologists, anthropologists, medical doctors, musicians, and economists. To all of them, we have shared our way of working and our approach to research (through making). We have pioneered such transformation so that the ministry of research is starting to consider adopting the name research-creation. Thus, we commented on these examples and how much the context is relevant to the research but pointed out another insight: the influence of the design research approach on other disciplines.

4.1.2.1 Case Study "Cornstalk-Based DIY-Materials"_Experiment Phase

We have chosen to focus the study on Colombia's peasant communities, particularly corn farmers, to demonstrate the effectiveness of DIY-Materials as speculative material prototypes capable of facilitating the visualization of possible and preferable alternatives.

Corn is an endemic plant in several regions of Colombia. As the uses of this plant widened, it began spreading throughout the country. Thanks to its high adaptability to different climatic conditions, it can be grown almost yearly at heights ranging from 0 masl (meters above sea level) to 3000 masl and precipitation ranging from 300 mm/year until 10,000 mm/year. Therefore, corn has a strong presence and tradition in all regions of the country. It is a vital energy source commonly grown by many families for self-consumption. For many years corn has been the most cultivated grain in Colombia.

The study looked at corn crop waste to show that it is a valuable raw material. Thanks to experimental research and field observation, it was possible to formalize guidelines facilitating the involvement of different community actors to create self-produced materials deriving from waste. In this case, prototyping using material drafts and demonstrators was the best way to approach farmers and demonstrate the potential of the sources they have very closed but not perceived as possible materials. Thanks to speculative material prototypes, we have also highlighted how these have an intrinsic nature to social innovation.

After analyzing the target context, it became clear that cornstalk, one of the most accessible elements in different regions of Colombia, is classified as the right choice for DIY-Material experimentation.

Tinkering with the material (cornstalk in this case) was the first phase of this experimentation. We achieved a small sampling scale which allowed many prototyping steps at a low cost in terms of time and material (Fig. 4.6).

The ingredients used were chosen to consider self-defined criteria based on the target context: accessibility, price, environmental impact, and processing energy. Economic ingredients were preferred that could then re-enter the biological cycle.

Self-produced material drafts were classified into six groups based on the primary alloying element used.

The next step was to test the performance of some draft material following standards that allow an objective evaluation of the results. The most promising for future

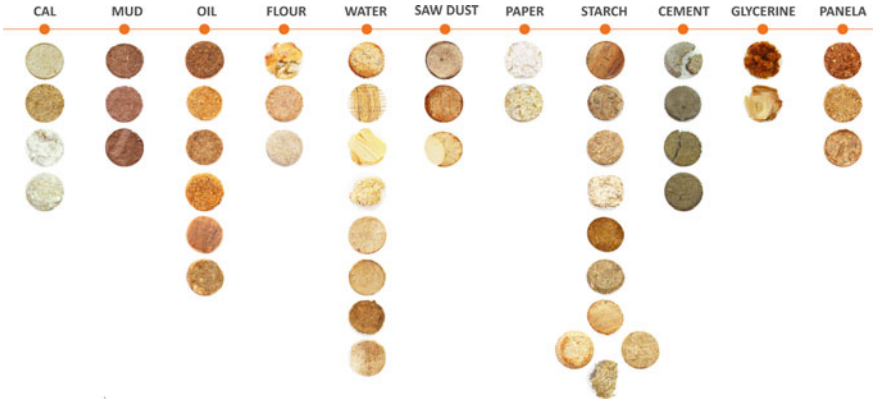

Fig. 4.6 Corn stalk-based DIY-Materials drafts produced during the tinkering phase

applications were selected from the fifty material drafts created. The parameters considered for the selection were solidity and resistance.

A second prototyping iteration was set to find the suitable composition of a material demonstrator to be tested with traditional standards for material characterization. The development of self-produced materials needs to meet not only the speculative part of the project but also demonstrate and promise feasibility. This is key in the prototyping phase, as it can show possible applications to potential users (Colombian farmers in this Case Study).

Moving from drafts to DIY-Material demonstrators, a first transformation test was performed using the most common processes employed in materials considered as references (cutting, sanding and perforation) (Fig. 4.7).

The next step was to run some standard tests to compare the performance of the material demonstrators against similar materials.

The DIY-Material demonstrators (SD1, W5, CS8, and CS11, according to the codes used in the material experimentation charts) were produced large quantities and marked with the material code plus a sub-index.

Summarizing some results, we can say that the demonstrators SD1 and W5 had the highest density, which are solid results for using the material in woodworking or carpentry. The transverse tensile strength of material sample CS8 was deficient because the material was made of alternating horizontal layers of different ingredients. Hence, the results show that these layers had low bonding strength. The thermal conductivity test was performed on one demonstrator of CS11. The results show excellent performance.

Although the laboratory characterization had a limited scope, it helped to validate the idea of potential uses for these kinds of corn stalk-based DIY-Materials. The performance of material samples W5 and SD1 can be highlighted and compared to industrialized material, but different from other materials used for the same purpose; such characterization shows the potential of use while the materials can be developed in the same place. It is important to recall that material demonstrators

Fig. 4.7 Selected material demonstrators for characterization

were developed based on an iterative process, and the characterization stage was performed on the second iteration of each demonstrator. The continuation of this process could keep improving the characteristics of these materials and widen their potential applications.

4.1.2.2 Case Study "Cornstalk-Based DIY-Materials"_Sharing Phase

Once we demonstrated how to develop DIY-Materials considering Colombian corn farmers' constraints, we used drafts and demonstrators directly in context to evaluate how speculative prototypes can be helpful in social innovation processes. We, therefore, planned workshops followed by a peer-to-peer conversation in which the knowledge and practical experience of farmers and their community further fueled the development of DIY materials (Sauerwein et al. 2017). The pluralistic and democratic characteristics of DIY-Materials were also highlighted, such as using local resources, practical experimentation and creating customized tools and methods. All these factors have made farmers and the community understand that this approach could become a commercial alternative where they do not have to face the traditional barriers of acquiring resources, knowledge, and technology. Tools such as videos, images, tangible examples, questionnaires and personal experiences have been added to each workshop to provide the best possible picture of the benefits this type of development could bring to the community.

Five workshops were held in three different Colombian rural areas for fourteen people of different ages and backgrounds (Fig. 4.8).

The findings of the initial encounter during the workshops supported the assumptions made regarding the wishes and needs that could motivate the development of social innovation projects.

For the hypothesis ascertainment through the workshop, farmers needed to understand DIY-Materials and how to produce them. Comprehending the aim of this type of approach and how a community strategy brings advantages for all is of extreme importance. Tangible examples of some of the corn stalk-based DIY-Materials made were presented with product examples, talking from first-hand experience and openly speaking about processes, ingredients, and tools used. Farmers and their communities realize their potential and capabilities when developing materials themselves. They also recognized the advantages and the wide variety of uses and applications this kind of material could have. This is key to converting speculation into a design alternative that was not devised before. The final iteration of prototyping with the community through material demonstrators opens new possibilities for the farmer to imagine a different future. Thanks to the awareness that a DIY-Material approach presents in terms of the availability of resources, moves towards a tangible model of project speculation. The groups identified business opportunities to create economic profit and local employment with relatives and neighbors with other skills like carpentry or manufacturing crafted goods. Even populate local diners, cafeterias, schools, and parks with products made from these materials.

From a community point of view on social business grounds, it was visible that even though the social interaction between farmers and their communities was different, all the farmers had a positive attitude towards sharing ideas and working with others. While developing small-scale agriculture, most farmers had already experienced how they could help each other farm, harvest, share knowledge, and enrich their social life. Therefore, they see work with others as a strength and something they would intuitively do to help each other. Furthermore, at an entrepreneurial

Fig. 4.8 Workshops carried out with farmers to show DIY-Materials out of cornstalk potential

level, it was clear to them that more people meant more resources, ideas, and skills, enabling them to go beyond covering individual needs to start a small business. "If you could make a small company, you could look for other people and other sources of waste", said Leonidas Bernal, a local farmer who attended one of the workshops.

To conclude, when collecting the data for the Case Study, we noticed that about the terminology the research team also used terms other than the prototype, that is;

- Experimental material samples, meaning the ones used in the first step of the research;
- Material Demonstrators, meaning the ones used in phase to show other stakeholders the refined result of the experimentation.

Furthermore, we reckoned the different prototypes developed under this project could be divided as follows:

- Experimental prototypes of materials with the base Corn Stalk (Italy): A series of iterative low-res prototypes (30 in total) where the researchers investigated the properties of the material and mixed different ingredients to produce a collection

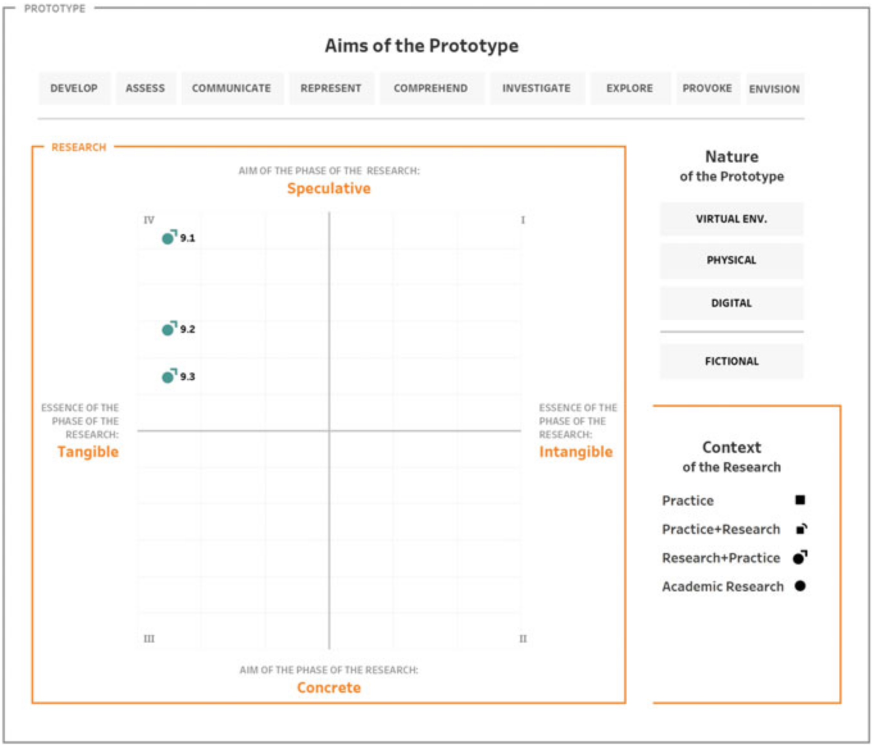

Fig. 4.9 Case Study "cornstalk-based DIY-Materials" displayed in the interaction tool

of material samples for evaluation. These prototypes were for the specific aim of "Investigate" (dot 9.1 in Fig. 4.9).

- Tuned-up prototypes of material samples (Austria): A selection of the six potential samples for laboratory testing. Once the prototypes were tested, minor improvements in the formulation and ingredients were made. These prototypes were for the specific aim of "Assess" (dot 9.2 in Fig. 4.9).
- In situ prototyping (Colombia): With a clear spectrum of the best choice to experiment with a corn stalk, a series of workshops took place with the Colombian farmers of selected towns to show in real time the different materials that can come out of the corn-stalk leftovers in their farms. These prototypes were for the specific aim of "Communicate" (dot 9.3 in Fig. 4.9).

All the dots are in the IV Quadrant (Fig. 4.9) as they aim to answer speculative questions within a tangible experience with materials. Also, the three dots representing the three groups of prototypes have a descending trend. This highlighted the progress toward concreteness and, thus, the role prototypes played in it.

This Case Study is particularly interesting in showing how the action of prototyping is itself a research activity that leads to a general understating of phenomena and creates new possibilities.

4.2 Discussion

The chapter described two cases in which prototypes were considered tools for dialogue and reasoning along the development process, thanks to their abilities to simulate hypotheses even if they are still blurred and undetermined. In both cases, the prototypes developed had an experimental dimension and were not generated for market purposes in the short term.

In these two case studies, the prototypes were considered a way of materializing the possibility between tangible and intangible matters. We tried to highlight the prototypes' opportunity to propose alternative futures, thanks to their characteristics to favor and facilitate speculation. Indeed, they appear in the top part of our framework scheme (Fig. 3.3) that refers to speculative studies.

As opposed to the accredited understanding of the idea of the prototype as the materialization of a possible solution that leads to technological innovation initiatives, speculative prototypes stimulate issues and allow the critical competencies of the participant to emerge. Speculative prototypes encourage us to move towards more experimental modes of designing futures together, considering the critical perspective and the tinkering practice as an activator of agency and social change. The speculative potential of prototyping—whether tangible or intangible—conceive solutions as questioning operations: to envision, provoke, and enable different perspectives and understandings to open up future possibilities.

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Chapter 5
Prototypes of Tangible Interactions

Venere Ferraro and Susanna Testa

Abstract As authors of this chapter, we aim to analyse the role of prototypes in the research area of interaction design. We selected three Case Studies involving tangible artifacts in the context of academic research. We interviewed Livia Tenuta, assistant professor at the Design Department of Politecnico di Milano, who shared a Case Study of research in innovative jewelry for an Italian company. We interviewed Olga Noronha, designer, artist and visiting lecturer at the Royal College of Arts and Central Saint Martins. She shared her doctoral thesis findings about an Investigation into the Possibilities and Affordances of Medical Jewellery. Thirdly we interviewed Tom Jenkins, assistant professor at IxD Lab IT, University of Copenhagen. He shared with us the Case Study of research on alternative modes of living thanks to domestic Internet of Things devices adopted in co-housing communities. All examples refer to research developed in an academic context, where external partners are involved at different levels and for various purposes. In the chapter, firstly we illustrate the selection criteria adopted for three Case Studies. Then we describe compare and discuss them through the lens of the prototypes' categorisation criteria and interviewees' feedback on our theoretical concepts.

5.1 Prototypes in the Tangible-Speculative/Concrete Design Research

The present text focuses on the analysis of the role of the prototype in the domain of interaction design, which is the process in which technology, products, and solutions are designed and shaped to centre on the human behaviour, interaction, and utilisation of a system(s) (Benyon et al. 2005; Moggridge and Atkinson 2007; Rogers et al. 2002; Saffer 2010).

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In the disciplinary area of interaction design, there are no more boundaries between the traditional disciplines of product, fashion, communication, and interior/spatial design since we refer to systems crossing smart products and clothes, digital and visual interfaces, and responsive environments. More in detail, the Case Studies here described and explored focus on the design of interactive experiences enabled and mediated by both analogue means and digital technologies between users and their bodies, users and other users, users and objects, and users and environments (Desmet and Hekkert 2007).

While dealing with human behaviour and users' dialogues with others and the surroundings, the role of the prototype in the design process becomes crucial. Indeed, the prototype is used to implement ideas into tangible forms, from paper to digital (Wiberg and Stolterman 2014) and to explore and assess new experiences (McElroy 2016).

When selecting the Case Studies, we kept in mind the four theoretical concepts concerning the use of the prototype in design research defined in Chap. 2. To recap, Concept 1 "Transition" described the prototypes as "the fundamental need to make magmatic and conceptually embryonic ideas manifest through fathomable forms of representation" (Sect. 2.3.4). Concept 2 "Making theory" described the prototype's role as means for reflecting on the design process. In that perspective the specific prototype(s) becomes proxies of theoretical instances to be put to the test to understand the dynamics related to the use of, e.g., materials, technologies, social interactions. Concept 3 "Evolution" related to the emergence of new prototypes and ways of prototyping connected with the technological digital revolution. Concept 4 "Milieu" described the relevance of the context in which the research takes place and highlights the academisation of the design research.

In light of such a theoretical framework, we selected the relevant Case Studies that could let us test such findings. We interviewed three colleagues in charge of their research and asked them to share their thought about our theoretical findings and the details of the Case Studies.

We interviewed:

Livia Tenuta, assistant professor at the Design Department of Politecnico di Milano, Italy, she shared the case of the design project "SmartJ. for Baraka";
Olga Noronha, designer, artist and visiting lecturer at Royal College of Arts and Central Saint Martins, who shared her doctoral thesis "Becoming the Body: An Investigation into the Possibilities and Affordances of Medical Jewellery";
Tom Jenkins, assistant professor, IxD Lab IT, University of Copenhagen about the research project "Cohousing IoT".

While selecting those case studies, besides using the four concepts related to the use of prototypes, we also considered what we, the group of researchers participating in the Project PARIDE, meant with the term *advanced* prototypes, that is "prototypes—resulting similar, in terms of aesthetics and functionality, to a finished artefact—that allow a researcher to test user experiences, providing helpful information for designing future scenarios" (see Sect. 1.1).

The first two Case Studies belong to the area of wearable devices defined as discrete electronic hardware mounted on objects designed to be "worn" (e.g., glasses, headgear, footwear, skin patches, handbags) (Ferraro 2021). In particular, they belong to those classes of fashion products that accompany people in their daily lives and have a strong link with the body. Therefore, the term *fashion* is understood in those case studies as "equipment for the body" (Farren and Hutchinson 2004).

In this view, the term *fashion* no longer alludes to the clothing industry but includes a broader number of categories of enabling products that act as body extensions.

The Case Study "Cohousing IoT", apparently distant from the first two, uses research through design to probe alternative modes of living and prototype domestic Internet of Things devices and propose new roles for internet-connected things to support and sustain the social life of a co-housing community.

The three explored Case Studies, therefore, in our opinion, well represented the broad view of interaction design and some of the contemporary trajectories for the sector as:

- they arose from the intersection of fashion/product and technological progress (enabling and requiring the creation of new types of prototypes);
- they operated experimentally in a dimension of complexity at the boundaries of heterogeneous disciplines, describing realities that are sometimes at odds with traditional practice (broadening its perspectives, fields, research methods, and uses of prototypes);
- they were projected towards a practice aimed at integration between disciplines, approaches, different skills and professionals, between products, enabling technologies and spaces, between products and the human body;
- they were targeted to improve human–human experiences (Case Study "SmartJ. for Baraka") and social aspects such as disability (Case Study "Becoming the Body") and co-housing (Case Study "Cohousing IoT").

Once the objectives and themes were defined, the three Case Studies were first described in terms of time frame, partners (institutions, companies, and organisations), people involved and their role in the project/research, overall research description, context, and disciplinary area definition. Secondly, we investigated the role of the prototype in the three studies through an interview addressed to the reference person and a description of each Case Study.

The first part of the interview explored the four theoretical concepts related to the use of the prototype (Transition, Making theory, Evolution and Milieu) and how those concepts can be reflected in the research practice.

The second part was based on a questionnaire that framed: the research phase(s) in which the prototype was used and aims for which they were made.

5.1.1 Integration of Digital Technology for a Jewellery Company

The combination of digital technologies and fashion has enabled a new lever for companies' success: creating an experience for consumers, who can acquire an active role by interacting in the process (Testa 2019). Livia Tenuta's research activity was set in this framework and, in particular, had the objective of defining a methodology able to combine the processes of fashion design and the engineering approach (Tenuta 2016). According to her research in the field of fashion technology, fashion design and engineering methods are currently applied alternately or in an imbalanced way, showing a lack of integration and dialogue between the two fields. Therefore, Livia Tenuta's work aimed to develop a fashion-wearable design methodology that could potentially embody authenticity. Her research indicated and analysed the limits of wearable technologies intended not only as products but also as a systemic and procedural dimension offered by a design-oriented approach. The experimentations on the methodology to design wearable devices gathered different workshop activities and industrial partnerships run at Politecnico di Milano. The Case Study here presented is part of the "SmartJ." project (Cappellieri et al. 2020) took design research out of the academic context to respond to market demands.

Interview on Theoretical Findings In relation to the first concept, "Transition" from abstract to concreteness, Livia Tenuta confirmed that, in her research practice, the prototype is the tool that allows magmatic and conceptually embryonic ideas to be made manifest through forms of representation that can be sounded out. Indeed, for Livia Tenuta, the prototype is the means by which to verify that all the characteristics and specifications identified in a conceptual phase can be applied to an actual physical product. Since this is a type of research aimed at investigating the relationship and interaction between body equipment and the body, the prototype takes on the role of a tool which, within the research, facilitates not only the transition from chaotic, confused and sketchy to clear and defined but also from abstract to tangible. Within her research, the prototype facilitates the transition towards materiality and realism: "We tend to make prototypes that are not 100% functional but realistic. Even if the final materials are not used, the experience of contact with the prototype must represent the real final experience". Although in this research the prototype describes this kind of transition, Livia explained that she is interested in and recognises the value of using the prototype as an enabling tool for a transition to the speculative and immaterial dimensions as well, especially concerning future scenarios and trends definition. In the concept "Making Theory", Livia Tenuta recognised within her research practice the importance of the prototype as a tool capable of going beyond its function of supporting the initial technical development phases. For example, the prototype becomes a useful tool for preliminary verification of the functioning of certain elements of the concept (going beyond materiality), but also a tool for making theory. According to Livia, prototypes are the result of a methodology that starts with research, goes through concept definition and ends with realisation. Learning by doing activities of carrying out practical actions contributes to creating theories and generating theoretical content—as in the case of the "SmartJ." project. With respect to the concept of *the emerging of new prototypes and ways of prototyping*, Livia explained that in her opinion the digital technological revolution has had an impact on the development of prototypes, this does not only concern the product, as in the case of integrated technologies, but also the production processes: she referred in particular to the technologies that allow interaction with virtual products thanks to augmented or virtual reality, or products with integrated technologies that generate physical responses and stimuli. On *the influence on the context on research activity*, Livia acknowledged that the role of the prototype is influenced by the context in which it is used. As a result, academisation and doing theory through practice have influenced the characteristics of the prototype itself and the research activity. This evolution has led to a more complex role for the prototype that can evoke discussion and reflection and can be used to test a theory and ultimately create new knowledge: Livia explained that in her practice the prototype is a tool not in itself but functional to something, it refers to the initial stages of research or concept development, and experimentation may not necessarily lead to a positive result. So, this iteration and validation through a physical or virtual prototype also helps to create knowledge through experimentation and testing.

5.1.1.1 Case Study SmartJewellery for Barakà

Description In 2015, Alberto Muraro, CEO of Barakà, an Italian company that caters to a male audience, turned to the research group of the Design Department of the Politecnico di Milano to develop a connected quantified-self bracelets collection. The group specialising in wearable technologies was coordinated by Prof. Alba Cappellieri and composed by Livia Tenuta, Valentina Bruzzi, Secil Ugur. The project involved a tech company responsible for the engineering part of the process. In particular, the brief of the project was to create a collection of technological jewelry pieces for people in business over 35, including mainly small-sized and precious bracelets without having the appearance of a gadget. For the Politecnico di Milano research group, it was an opportunity to test the co-creation methodology between fashion designers and engineers in actual practice. The research was organised in the following phases: (i) the brand study, encompassing formal and material aspects, product type, and target audience hallmarks; (ii) market analysis and potential competitors; (iii) identification of existing technologies that could be combined with jewelry; (iv) scenarios and concepts development; (v) design of the products of the collection and their features; (vi) products realisation. After the first preliminary phases (i and ii), available technologies on the market were investigated and divided into three categories to simplify the approach to technology: input, output, and data transmission. Instead, more challenging research was carried out for batteries representing one of the most significant limits in size and duration.

Based on existing technologies, three possible scenarios were identified:

- Bracelet > smartphone > bracelet: the bracelet was the tool that received inputs from the environment or the body, transmitted the data to the smartphone reworked them, and sent the output to the bracelet. For example, the jewel monitored the heartbeat, the mobile phone stored the received data, recorded that the beat was regular, and sent the signal to the bracelet that communicated information to the user through a sound, a vibration, or a light signal.
- Bracelet > smartphone: the bracelet was the input to activate a function on one's smartphone. For example, by contacting the bracelet and the smartphone, one could access private data.
- Smartphone > bracelet: the phone received the input, displaying the output on the bracelet. For example, the user could get a call on the smartphone, and the signal was also sent to the wearable device.

Based on the analysis, a collection in which all the products had common characteristics was designed. The technology part could be easily removed and replaced to be updated directly in Barakà boutiques, making the user-brand connection increasingly closer. All scenarios relied on the Barakà app to alert the user when a new product and latest updates were released. All jewels were thought not to have a seasonal duration but to resist the passage of time, be updated and customised according to the tastes, but always following the brand's aesthetic. From the direct experience of the physical realisation of the design, some difficulties in developing miniaturised technology on a small scale emerged. Because of the challenges mentioned above, the product did not reach the market right away (but only a few years later). Indeed, it required more investment to solve miniaturisation challenges. The process led to consideration in terms of methodological approach, and a clarification of the roles and expertise needed. This project, together with other experiences in the field, led to the tentative development of a hybrid methodology that combined some elements from both the fashion design and the engineering methods. The two approaches were combined to tackle problem definition and investigate user needs and desires, the fashion market, current trends, and innovative technologies that were ready to be applied to industrial production. The initial definition of basic requirements was followed by the most creative part of the project, in which brainstorming led to the generation of a specific future scenario. Products were centre stage and become the focal interaction point between users, the environment, and other objects. Equally important, nonetheless, was the correct identification and analysis of specific personas on whom to tailor the project. These steps were crucial to set the project on the right course: the procedure enabled designers to identify with a specific set of users and understand their needs and issues to develop the original project. The proper management of the two stages positively affected the following definition of a precise concept. It also eliminated the widespread inclination to equip objects with too many functions and even enhanced the relationship between their shape and function. The concept stage witnessed the identification of materials, shapes, and interaction dynamics by means of technical sketches. Later experimental prototypes were completed, tested, and evaluated. Qualitative checks, typical of the engineering approach, were in place and matched by a qualitative assessment that tested user

Fig. 5.1 Project SmartJewellery for Barakà. Credits Livia Tenuta, Politecnico di Milano

experience by measuring the intensity of the users' emotional response to product interaction. All these steps had to be managed by designers and technology experts, as only the joint application of their respective skills may lead to successful products (Fig. 5.1).

Data Collection and Analysis The principal investigator of the project, Tenuta, told us that no other term was used by the research team to refer to prototypes.

Regarding the project phases, she highlighted that prototypes were mainly used in the conceptualisation and design development stages.

The concept of "Fidelity" in describing the prototype was applied and referred to as medium fidelity.

The specific aims selected by the interviewee applied to the use of the prototype within the research 'SmartJ. for Barakà' were the following ones: develop (finalise design and resolve), assess (test, evaluate/analyse, improve), communicate (persuade/reassure, show, get feedback), represent (visualise), comprehend (understand, collect (data)), research (produce (knowledge), translate (abstract to concrete), identify (problems), investigate (issues), explore (experiment, experience), provoke (discuss (critical)), foster (imagination/creativity), anticipate).

When later we asked to group prototypes with similar aims in different stages of the research process (see Sect. 3.1.3.4) Tenuta highlighted three groups. The *first group* consisted of 3D models and realistic rendering of the object used within a scenario (however they were defined with the term 'models' not 'prototypes') with the aim of fostering imagination (envision). They could be digital and visual, virtual and fictional. Indeed this group was displayed in the IV Quadrant of the interactive tool (dot 5.1 in Fig. 5.2). These were employed in an intangible phase of the research with a speculative scope. The *second group* referred to aesthetic prototypes by verifying that all features and specifications identified at a concept stage can be applied to an actual product (therefore to finalise design). These prototypes were not 100% functional, but they were physical and realistic. They were made from materials that were not the final ones but resemble them, and the experience of contact with the body had to represent the actual final one. They were used in a tangible and concrete phase. The *last group* dealt with physical prototypes that provided for technological

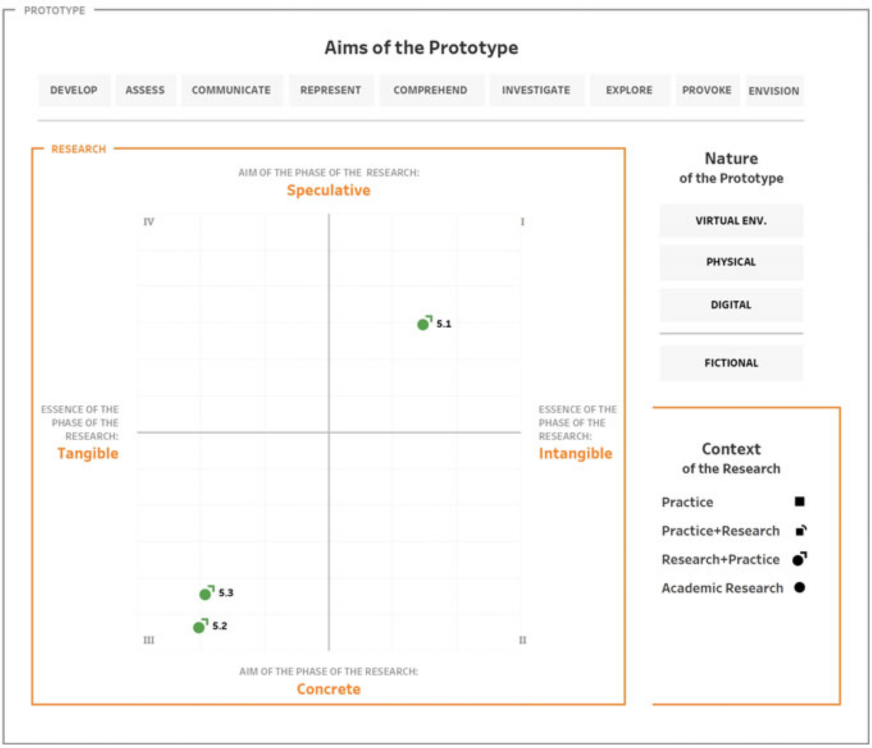

Fig. 5.2 Case Study "SmartJewellery for Barakà" displayed in the interaction tool

integration. Therefore, as in the previous group, the phase in which they were used in it was tangible and concrete. These two groups were displayed in the III Quadrant of the interactive tool (dot 5.2 and dot 5.3 in Fig. 5.2).

To summarise, 'SmartJ. for Baraka' research moved in a tangibility dimension and had concrete objectives: developing an innovative project for an actual company. Even though a speculative phase was held to envision possible solutions before the design. The prototypes were essentially physical and used in the project development phase.

5.1.2 Exploring Possibilities and Affordances of "Medical Jewellery"

The multidisciplinary research areas that animate the complexity of contemporary fashion include the scenario arising from the integration of medicine, orthopaedics, and projects investigating the relationship between disability and aesthetics. The results are objects suspended between ornament and medical function and define a new relationship between the traditional image of illness and physical defect and a unique, intimate idea of beauty. Olga Noronha's research practice analysed the intersection between anatomy, medicine, and ornamentation and explored the concept of "jewellery as prosthesis." In "Becoming the Body: An Investigation into the Possibilities and Affordances of 'Medical Jewellery'" (2018), she proposed a vision of implanted prostheses being transformed into intra-body jewellery.

Interview on Theoretical Findings With respect to the first concept, *the transition from abstract to concreteness*, Noronha recognised in her research the role of the prototype as an instrument capable of making magmatic and conceptually embryonic ideas manifest through forms of representation that can be fathomed. It is a process of ideation and materialisation, and therefore a path towards the tangible. In particular, for 'Medically Prescribed Jewellery', she talked about 'advanced and accurate prototyping', which can be computerised or manual. Noronha has a particular schematic that she follows, and she needs to base her prototypes on the dimensions of medical products, on the application of those medical devices and the anatomy of the human body. So, tangibility here is not conceptual but technical because she produces something that then has to be tested mathematically, quantitatively and qualitatively. When asked to place her research activity in the realm of 'material and realistic' or 'speculative and immaterial', or crosswise—she replied that with Medically Prescribed Jewellery she created speculative objects that are prototypes for realistic approaches. She recognised the value of a type of approach linked to the use of intangible prototypes, as in the case of using the telling of a story (intangible and imaginative) as a form of prototype for testing with possible patients—but said that most of the time she would show an image, so the impact is different, and the tangible aspect is on an image. Reasoning on the second concept, Noronha argued that *making theory* is a prerequisite for her prototypes because they are epistemic objects, they are enriched when they gather knowledge. They present knowledge and frameworks that then allow her to further develop a project through those objects. With respect to *the emerging of new prototypes and ways of prototyping*, Noronha acknowledged the impact that the digital technological revolution has had on the development of prototypes at different levels. However, she claimed to have no particular knowledge of 2D or 3D projection. She prefers to represent things in drawings and modelling to actually have the dynamics of touching perception. She does not use these types of technologies for most of her work. As for "Medically Prescribed Jewellery", she has not yet tested the products, but they have to be tangibly tested in the laboratory. Noronha pointed out that these are complex prototypes and because of their nature they require the coordination of different professionals: from a technical point of view, the medical jewellery has to go through a laboratory, engineering universities and biomechanical engineers. The consumer experience was very difficult to test: Noronha said that, within medical products, when you think about health recovery, you can't really talk about consumerism and experience. In fact, the aim was to achieve a balance, in this case, between the aesthetic and psychotherapeutic aspects of what she was offering, and the fact that it actually worked as a real medical device: the aim was to heal—to help mentally and to heal physically. It was not within her competence to be able to test them, but it required many other professionals. Olga Noronha's objects are unstable objects because they can be seen in different ways depending on the context: they can be seen as medical prototypes, sculptures that talk about medical devices and the body, or design products. They tell a story and can be exhibited in a gallery or a museum, in which case they can be taken either as finished objects or as prototypes. At different times, they can be suitable for different purposes: aesthetic prototypes and functional prototypes where functionality requires much more expertise than just the person who created that idea. Lastly, Olga recognised *the influence on the context on* her *research activity*: there are places that consider design research as a mathematical production process, and other places that take design research as a creation of philosophical knowledge about the object and the user experience and the way people act and interact with design. Olga said that she developed the concept independently, and developed the aesthetics and materialised the concept influenced by the field and context she was in. And then, while doing her M.A. and Ph.D., she was influenced by a College context that was much more into anthropology and philosophy.

5.1.2.1 Case Study "Becoming the Body"

Description The research was developed between 2011 and 2018. It took place at the Arts and Humanities Research Council. It started at Central Saint Martins for one year, and then it went on at Goldsmiths University. Noronha was the design researcher and head of the project. To develop the research project, she collaborated with patients (physically vulnerable people), doctors (such as orthopaedic surgeons), and mechanical engineers in Portugal. The research investigated the social and psychological aspects of body modification and medical interventions on and in the body by analysing biomedical research into the repair of the body, surgical procedures, material compatibility, and prosthetic design. Noronha then outlined the theoretical underpinnings of the work, the necessary practical-material considerations in producing 'viable' medical jewellery, and the understanding of its reception in different contexts (medical and jewellery). She suggested an alternative way jewellery could operate by adapting the perception of medical repair (from wound stitching to joint replacement) and inquiring about the feelings/perspectives of the body when repaired. The work had come about by considering sites on and in the body at different 'archaeological' layers (from outer to inner physical space), namely orthotics subdermal, exodermal, exo-corporeal intracorporeal jewellery. These layers presented a series of "medical jewels" that recognized science, jewellery, and technology as accomplices to repairing and enhancing the 'self' while adding value to the mended body. Rather than only a medium for expression, the repaired or fixed body became a locus for experience, symbolism, and aestheticization. The jewel is understood to both aestheticize the body (it becomes you) and become integrated and integral to the body. In this research, "Becoming the Body" indexed an aesthetic enhancement of the body; naturalisation in the body—as a body replacement or part of it; completion or repair of the body, and a prosthetic enhancement. By moving jewellery into this space (namely surgical repair), the research and its practices tested the boundary/edge of what jewellery is and is not, what it may mobilise, and how it may perform. Also investigated how different publics received the work and how it moved through and across different epistemic constructs (art and science). The *discursiveness* of the practice was defined by understanding how the different designs performed in different situations, provoking and raising questions that were both specific to and cross-contrasting scenarios. The research had a twofold objective by intending to minimise or deflect the negative and mutilating effect inherent to medical repair. From one side it aimed to comprehend how the speculative medical jewellery—seen as tangible results of the aestheticized scientific technology and medical knowledge—was emotionally and physically experienced; from the other, to understand the knowledge they could gather and convey. During this doctoral academic research, Noronha was not fully developing the artefacts/medical objects but was doing research led by practice. She was reflecting on the practice she had already carried out to understand the response from different fields toward the concept and objects she had created. So, it was understanding how those objects of medically prescribed jewellery could open many other possibilities in science, design, and art (Fig. 5.3).

Data Collection and Analysis Olga Noronha, when asked about the terminology adopted to refer to prototypes, stated that she would call them 'prototypes' only at a very high stage of inquiry. She would refer to these also with the term 'models':

Fig. 5.3 Project Becoming the Body. Credits Olga Noronha

rough and simple paper models to catch dimensions and material tension. However, instead, she would call them ‘artefacts’, because that was actually how they were sold to clients, ‘limited edition artefacts.’ These ‘final artefacts’ were anatomically perfect items but not implantable and usable as medical devices.

The prototypes in the mentioned research were usually used in the design development phase, while fidelity was an implicit attribute for her.

The aims for which prototypes were used ranged from developing (finalising design, creating/designing), assessing (testing, evaluating/analysing, validating, improving—she would pick something that already existed and then adding something new), to communicating (getting feedback, conveying), representing (simulating, visualising), comprehending (understanding), researching (producing (knowledge)), exploring, provoking (investigating, speculating), and envisioning (anticipating).

When later we asked to group prototypes with similar aims in different stages of the research process (see Sect. 3.1.3.4) Noronha highlighted four groups of prototypes. The *first group* consists of realistic photomontage or realistic 3D generated images together with a story (conceptual tangibility). This first group of prototypes helps in gathering responses, and then the research continues with the project development and the creation of the “final artefacts”. The aim of this first group of digital (and visual) and fictional prototypes is to get feedback (communicate). The essence of the phase of the research is mainly tangible and its aim is speculative. Indeed, this group was displayed in the IV Quadrant of the interactive tool (dot 7.1 in Fig. 5.4). The *second group* (conceptual tangibility) is represented by study-sketches and drawings—physical prototypes that are used to support the creation within the development phase. The essence of this phase is tangible and mostly concrete. Moving to the *third group*, this relates to model making: rough and simple paper models just to catch dimensions and the material tension to actually have the dynamics of the touching perception (conceptual and technical tangibility). They are physical prototypes used with the scope of finalising the design. As in the case of the second group, the essence of the phase in which they are used is tangible and mostly concrete (technical tangibility). These two groups were displayed across the III and IV Quadrant of the interactive tool (dot 7.2 and dot 7.3 in Fig. 5.4). Lastly, the *fourth group* is represented by physical realistic final artefacts with accurate aesthetic qualities, such as the weight and the way it is positioned as an object in terms of scale or dimensional balance. It might be in that case computerised or manual, but usually manual. They are adopted with the purpose to evaluate/analyse (asses) in a tangible and concrete phase of the research. This group was displayed again in the IV Quadrant of the interactive tool (dot 7.1 in Fig. 5.4).

Olga Noronha’s practice, presented a type of research with a tangible essence (investigation and design in the field of medical jewellery), characterised by both speculative and concrete objectives: on the one hand, to investigate, envision and speculate on possible future scenarios for medical jewellery, to generate knowledge and provoke, but also to develop aesthetic and plausible artefacts in their functionality, to test the emotional and physical response of possible patients.

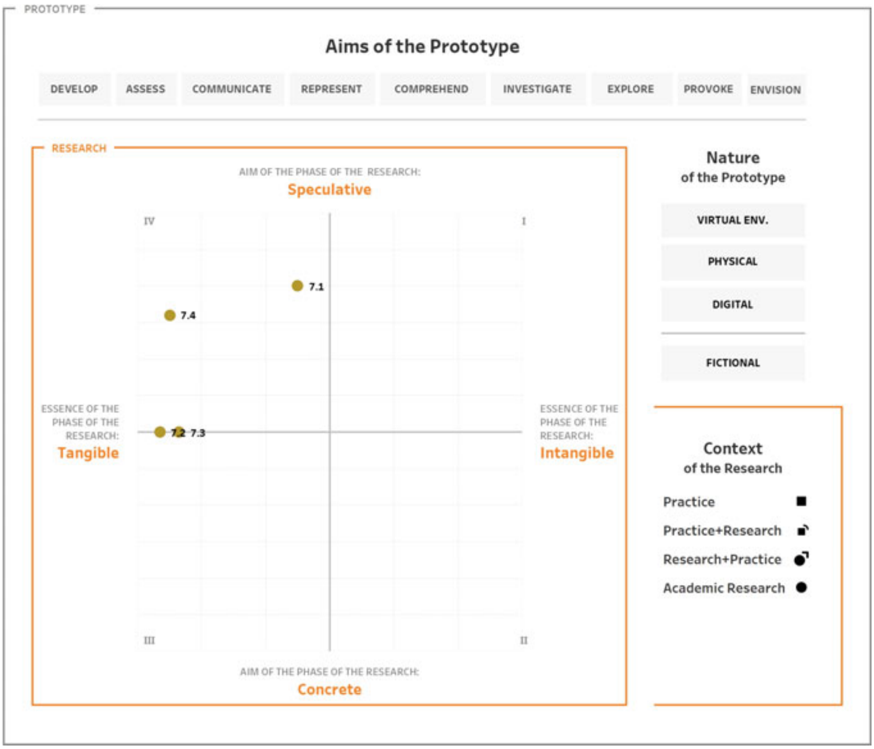

Fig. 5.4 Case Study "Becoming the Body" displayed in the interaction tool

The prototypes she used were mainly physical (she called them 'artefacts') and used for developing, assessing, and communicating during the research's development phase.

5.1.3 Prototyping Internet of Things (IoT) Devices for Co-housing Communities

Interview on Theoretical Findings Tom Jenkins explained how the four theoretical concepts interlaced his research. Concerning the first concept, "Transition" from abstract to concreteness, he said that in his opinion, being the prototype a filter for the design activity—it embraces the concept of transition, and its nature (physical-digital) depends on the type of the idea you are developing. For instance, it could be a sketch, a collage of images or a rough model to explore the form giving. Moreover, according to him, the nature of the prototype depends on its purpose so that it could be an image, a tiny model, or even a material sample.

Concerning the topic of the research placement, if in the material and realistic realm or the speculative and intangible one, he stated that his research is across the two words. From his point of view, the prototype objects represent "matters of concern" (i.e. a social one): they tell a story, and by doing so, they are an expression of reality. That said, they could both be used to be a manifestation of an idea or to speculate. For instance, if "we prototype to speculate existing technologies, we create new configurations of infrastructures and materials. Indeed, the prototype generates new contexts for existing products and services as well as new understandings of how they might operate in different social worlds".

Moving to the concept of "Making Theory" through prototyping, Jenkins explained that, in his opinion, the prototype is a valuable "thing" to carry on theory but also to concretize it. Besides, the prototype is useful for adding and generating theory/unique knowledge. About the knowledge, he believes that it is encapsulated into the prototype itself that being unique is a demonstrator of new knowledge (i.e. understanding how to change user behaviour).

While discussing the topic of *the emerging of new prototypes and ways of prototyping*, he confirmed that the role of the prototype has certainly evolved thanks to the digital revolution and that it is now part of each design activity (both in practice and in research). In light of the technological signs of progress, he believes that in our digital era, we should all have competencies in making prototypes using Arduino or unity, mainly because the competencies are shared among the teams of researchers.

Finally, about the concept of *the influence of the context on research activity*, he agrees that the context influences the research activity and, consequently the nature and the role of the prototype. At the end of the interview, we discussed the academization of the design discipline, and, in his opinion, prototyping is becoming part of the design discipline. Still, it is a bottom-up phenomenon rather than a top-down one. He doesn't see academization. He said that "prototype is both a manifestation of an idea, so it is related to the practice and then to the education and a manifestation of a design research activity". He finally suggested an exciting definition for the prototype: "prototype as a provisional thing", a contemporary sentence that embraces most of the concepts elaborated within the research project PARIDE.

5.1.3.1 Case Study "Cohousing IoT"

Description Cohousing IoT was a Research Through Design project that prototyped social Internet of Things (IoT) devices for co-housing communities. It was developed in 2018 at the Georgia Institute of Technology under the supervision of Tom Jenkins, now an Associate Professor at ITU of Copenhagen (Jenkins 2018).

One of the main objectives of the research was to speculate on domestic IoT devices. By developing three tangible working prototypes, it wanted to imagine alternatives to existing arrangements of things and devices in the home. The prototypes were used to envision new roles for internet-connected things that supported and sustained a co-housing community's social life. The development of the speculative prototypes went through a deep analysis made up of interviews, site tours, and attending everyday meals. Such activities provided different perspectives on co-housing, and thanks to them, it was possible to understand how shared life is lived and practised. Furthermore, the research project prototyped speculative technological systems to create new infrastructures and materials configurations. Three systems were prototyped to instantiate new social forces arrangements, not simply to have objects themselves. In detail, the researchers developed a community-based radio system, a platform for RSVPing to common events, and a device to help residents reflect on community participation.

The Cohousing Radio was built to connect residents in co-housing in a new, socio-material way; it imagined each residence with a small radio placed in the home. Residents can use this device to send audio files to other community members.

The Physical RSVP provided co-housing residents with a way to respond "materially" to invitations to events within the community. Every resident could register their intent to attend the event by placing a clay ball in a bowl; this way, the event's organiser could plan for the correct number of people. These balls were equipped with an NFC red by an Arduino-based reader on the underside of the prototype. Thanks to the Arduino, a notification was sent to a shared community calendar to update the attendance.

The last Cohousing IoT prototype was a set of scales that helped a resident reflect on their participation in the community. In the Participation Scales prototype, the position of the scales' arms represented an individual household's level of involvement in the community (i.e. attendance at events, work hours, and so on). This prototype was envisioned to shift current ideas of domestic IoT to monitor the home's condition to understand the needs of your participation in a community. The three speculative prototypes aimed to articulate current issues in co-housing while simultaneously proposing new opportunities for community collaboration via smart home technology (Figs. 5.5, 5.6 and 5.7).

Fig. 5.5 Cohousing IoT prototypes. Radio prototype. Credits Tom Jenkins, IT University of Copenhagen

Fig. 5.6 Cohousing IoT prototypes. RSVP prototype. Credits Tom Jenkins, IT University of Copenhagen

Fig. 5.7 Cohousing IoT prototypes. Scale prototype. Credits Tom Jenkins, IT University of Copenhagen

Data Collection and Analysis Tom Jenkins was very clear on the role of the prototype. He stated, "The whole project is about the prototype. The prototype is specifically used as a transition (from abstract to concrete) to make people understand".

When it comes to terminology, there were no other used terms; the word "prototype" was the only recognized one.

Regarding the phase, the author declared that the three prototypes were used in the conceptualization and detailing phases while the fidelity was obviously high.

In the Cohousing IoT research, the prototypes had different aims, namely: to develop (finalise and create/design), to assess (evaluate and validate), to communicate (show, get feedback and convey), to represent (simulate and embody) to comprehend (share/negotiate and collect data), to research (produce knowledge) but most of all, to speculate and anticipate future scenarios. Indeed, as described, the main objective of the Research Through Design project was to use tangible prototypes to speculate new Internet of Things devices.

This Case Study is a very peculiar one since the research was based on interviews, site tours, and researchers attending everyday meals, just one class of prototypes was developed to reason on speculative scenarios.

While discussing with the principal investigator Tom Jenkins, it arose that the essence of research was highly speculative (it was marked as 5) while the nature of the prototypes was both physical and digital.

The aim of the prototypes though the overall research was in fact to be as tangible and interactive as possible to be used and tested by the residents and help the research groups to envision new scenario for the IoT devices.

The usage of the three prototypes in engaging in multiple ways offered advantages in terms of *thinking through co-housing* as a space for smart home technology design. Briefly, the essence of the research was to speculate about the role that computing technology can take on in that living together (Fig. 5.8).

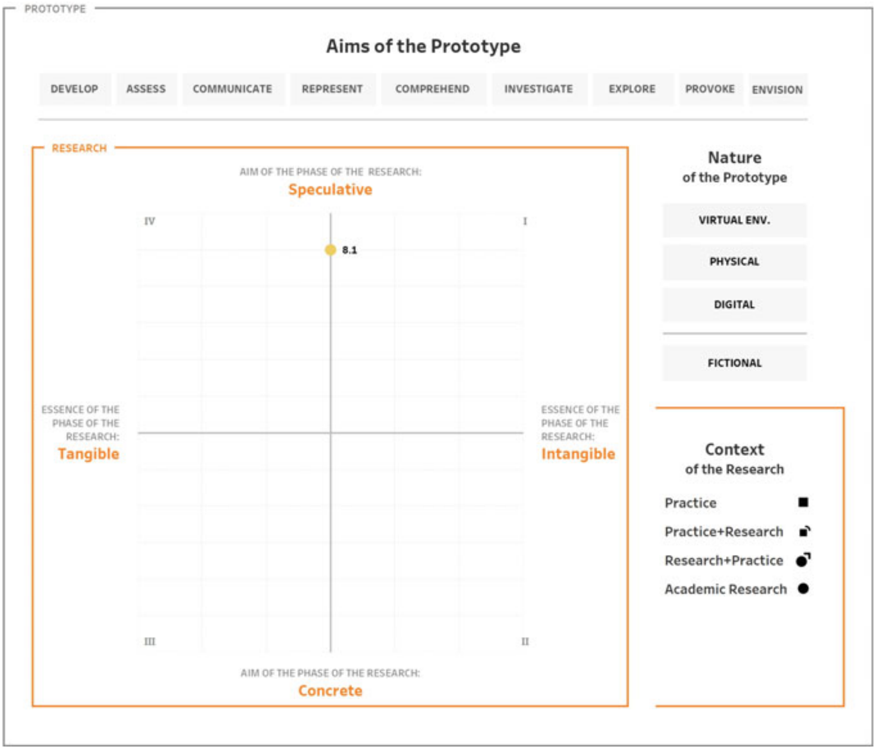

Fig. 5.8 Case Study "Cohousing IoT" displayed in the interaction tool

5.2 Discussion

After sharing all interviews and Case Studies, we—the research team of the study PARIDE created an interactive tool to display the Case Studies (Fig. 3.4). In such visualization, the three Cases presented in this chapter corresponded "SmartJ. for Baraka" to no. 5; "Becoming the Body" to no. 7 and "Cohousing IoT" to no. 8.

As the dots on the tool the represented group of prototypes made for the same step/aim of the research, we could see that most of the prototypes for these cases are tangible, with an exception for number 5.1 (in Fig. 5.2) that was a speculative phase based on visual models.

"Becoming the Body" and "Cohousing IoT" fit into the speculative area of the tool while the other two groups of "SmartJ. for Baraka" belonged to the concrete area.

Selecting the objectives of the three Case Studies one by one, we found that most of the points on the interactive tool (Fig. 3.5) belonged to the first two objectives, namely "develop" and "assess" (4 develop, 2 assess, 1 communicate, and 1 envision).

Even if the two academic research Case Studies ("Becoming the Body" and "CoHousing IoT") were placed in a more speculative dimension, and "SmartJ. for Baraka" Case Study was oriented towards a context of concrete practice (precisely because it is based on collaboration with a company), there were phases that cross the graph and break these patterns. This is the case, for example, of the first group of "SmartJ. for Baraka" prototypes which was in the I Quadrant. This showed how speculative and fictitious approaches in design research can also be useful for practice-oriented (concrete) research. Or vice-versa, by exploring "SmartJ. for Barakà", "Becoming the Body" and "Cohousing IoT" research projects, we discovered that medium and or high-fidelity prototypes that apparently might be used for concrete (close to market) projects were actually developed for speculative and envisioning reasons.

When we observed the trends highlighted in Sect. 3.2.3 (Fig. 3.5), with regard to the objectives of the research phases, we noticed that two of the three Case Studies moved down towards concreteness and from right to left toward more tangibility, but then both come back up for reflection even though in different quadrants. This shows that the role of prototypes is to make the idea more concrete but also to tend and evaluate the research towards theoretical results. Indeed, as said, while one, "Becoming the Body", is purely academic research, the other, "SmartJ. for Baraka", is an academic study for an industrial partner. So, it was interesting to notice a similar path but in different areas of the tool that corresponded to the different context of the studies and, possibly, to the different research questions and, thus, role of the prototypes accordingly. While the Case Study "CoHousing IoT" remained mainly in the realm of speculation, meaning that all prototypes used here share the same main aim.

"Prototypes (Greek *protos* = first) are intended to test the function and performance of a new design before it goes into production. Traditionally, prototypes represent one of the last stages of the product development process before the product is industrially manufactured" (Erlhoff and Marshall 2008).

While this definition refers to a outdated idea of prototypes and the role they play in design research, nowadays prototypes can be intended as anything that takes an idea from our head and makes it visible to others. In this wider perspective the three Case Studies here described and analysed confirmed a more complex and refined meaning connected to the word "prototype" or, better, to the activity of prototyping.

We can prototype to communicate the idea to others or test with users, with the intention to improve that idea over time, discover new solutions, and envision and speculate future scenarios. The Case Studies analysed in this chapter concerned research from academia or from fields that combined research and practice and covered different facets of interaction design. They are united using mostly physical prototypes that are employed in research whose essence is mainly tangible.

They represented the evolution of design research that, on one hand, brought speculative steps into studies for companies, where prototypes supported the integration of design and technical aspects toward the concrete making of new smart jewellery. On the other hand, design research crossed boundaries connecting medical devices to artistic speculation into the making of provisional objects that would never be mass manufactured but sold as art pieces. Nonetheless design research investigated possible interactions among community of co-housing habitants through that making of working prototypes that could be experienced by the user but were meant to test hypothesis not to create new products. So, in the realm of interaction design, tangible prototypes support research for practice and speculation focusing in particular on the possibility to gather user reaction to new solutions and possibilities.

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Chapter 6
Prototypes for Industrial Design Research

Silvia D. Ferraris and Lucia Rampino

Abstract As authors of this last chapter, we provide our point of view deriving from our disciplinary background in industrial design, design innovation, and design engineering. We selected four examples that would give us a broad view of the use of prototypes in the product design area of innovation and engineering. First, we interviewed two academic colleagues: Sara Colombo, now an Assistant Professor at Eindhoven University of Technology, shared an example of research she developed in collaboration with a large industrial company while working as a research project lead at MIT Design Lab. Pieter Jan Stappers, Professor of Design Techniques at T.U. Delft, shared a milestone doctoral thesis in theorizing the Research Through Design approach. Their examples covered top technical universities' "research + practice" and the "academic research" contexts. We then interviewed two practitioners presenting us with award-winning projects where prototypes played a crucial role in design research. Marco Meraviglia, a designer at Cefriel, extensive engineering and design research center, presented a project falling into our definition of "practice + research." Gabriele Diamanti, the cofounder of Ddpstudio, which matches our context definition of "practice," presented us with the case of a small design studio participating in a large, applied research project.

6.1 Prototypes in the Speculative-Intangible/Tangible Design Research

6.1.1 Exploring Possible Futures with a Large Company

During the interview, Sara Colombo described her experience as a researcher at MIT Design Lab, where she said they did speculative and practice-oriented research. Indeed, they collaborated with companies representing fields of investigation for which they generated visions of how emerging and future technologies can be applied

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to and can transform specific contexts or application fields, focusing on users and their experience. We registered her input accordingly across two definitions "research + practice" and "academic research."

Then, we asked for her opinion on our theoretical findings, which were the four Concepts: 1. Transition, 2. Making theory, 3. Evolution, and 4. Milieu.

In the first concept, "Transition," we stated that prototypes "*serve the fundamental need to make magmatic and conceptually embryonic ideas manifest through fathomable forms of representation.*" Colombo agreed that—in her experience—this transition is fundamental, but it varies on the type of research, becoming more relevant in design fiction. In this case, the MIT Design Lab developed visions of the future in five to ten years, or even more. To this end, the support used to convey the future design to the partner companies entails physical prototypes, provisional objects, videos, and storytelling, depending on the research phase (and the aim of such phase).

Often the physical prototypes did not work entirely, especially if they employed a future technology that was not available yet. In any case, the prototype must be able to communicate the main product features. Therefore, the idea of *transition* from the concept of what they imagined as a future solution to a more tangible thing was fundamental. In other cases, the prototype was more of a creative tool than a descriptive one, supporting the development of the first idea. In such cases, according to Colombo, there was not a *transition* from a very structured concept to a prototype, but rather it was the prototype itself that evolved. In other words, an initially loosely defined concept was gradually finalized while working on the prototype.

Always regarding the concept of "Transition" (see Sect. 2.3.4), we asked Colombo to position her research activity between the opposite poles of "material and realistic" or "speculative and intangible." She answered that they did both "material and realistic" and "material and speculative" research at MIT Design Lab, rarely intangible. The most intangible they came to was perhaps a sketch of a story of their idea that they could call a "prototype," although it was still very conceptual.

So, in the case of research that aims to describe possible future designs (i.e., design fiction), the prototype helps to develop the idea and makes the imagined concept into a communicable and sharable form. In this case, the transition from abstract to concrete is not just to represent the idea but also to explore its potentiality. Indeed, in her research activity at the MIT Design Lab, Colombo aimed to draw the path for future developments rather than realize a solution that shall become real in the immediate future, as in practice-oriented research.

In the second concept, "Making theory" (see Sect. 2.3.4), we said that the prototype has taken on the role of means to reflect on the design process. Colombo commented that, working at a research institution, the importance of knowledge creation and sharing is unquestionable. Indeed, in most cases, they created detailed reports that, in addition to describing the whole design research process and outcomes, discussed the results at a more strategic level, to give an idea of how their partners could approach specific contexts in the future. Knowledge was also often shared with the scientific community through publications. Finally, for the researcher, building personal knowledge was relevant. Colombo affirmed that, when creating a speculative prototype, she tried to envision what consequences it could have in the future, imagining the usage scenarios and their impact on people at the individual and social levels. This approach helped her create mental infrastructures that she could apply to other projects.

The third concept, “Evolution” (see Sect. 2.3.4), was intended to underline that, as design is undergoing radical change, the digital revolution has impacted the development of prototypes on several levels. Colombo confirmed that, in her experience, the drive of technology—and its integration with design—was persistent and crucial.

The last concept, “Milieu” (see Sect. 2.3.4), emphasized that the role of the prototype has evolved with the context in which it was applied. From one perspective, it was reckoned that prototyping is a cognitive repertoire of design skills. In the sight of this, the prototype supports the idea that design can generate knowledge through making, that is, by developing design concepts and theory out of this process.

Colombo commented that, in her work at MIT Design Lab, the prototype was often a research result. Indeed, the kind of prototype they generated was rarely at a level detailed enough to be put on the market as is (which was also not their primary goal as a research lab), although sometimes it was aimed at creating a product that could be further developed and commercialized by a company in the near future. However, the prototype was still a fundamental part of the research process. Without it, a substantial piece would be missing because research seldom was purely theoretical in their research group.

During our research, this last statement helped us frame the idea that the context where the study takes place was crucial for the role of the prototypes. We then discerned from the context (“research + practice,” “academic research,” etc.) and the “aim of the research” speculative or concrete, which meant for us “far or close” to becoming real and reaching the market.

6.1.1.1 Case Study “Augmented Health and Safety: Future Vision”

This research took place at the MIT Design Lab in 2017 (Colombo et al. 2018). It was a one-year project. Sara Colombo selected this research project, among others, as it represented an extensive and integrated use of different prototypes in the context of quite complex research.

The research was done in collaboration with an industrial partner, a global energy company. The aim was to foresee how emerging technologies may transform health and safety practices in the energy industry in the near future.

The research approach was based on design fiction, where a future scenario was developed through designing and prototyping a system of physical and digital solutions addressing health and safety problems. The research outcome was an integrated vision made up of seven concepts. Some were tangible solutions (Deep Vision Shield, Sensing Suit, Active Glove, and Robotic Inspection), for which a physical prototype was built. These prototypes were non-functional mockups. Other concepts were immaterial (digital) solutions (Worker Profile+, Health Chatbot, Advanced

Hazard Detection), for which the research team created UX prototypes. Also, they made some videos to explain the ecosystem of the seven concepts and how they were connected. Furthermore, for the Robotic Inspection, Deep Vision Shield, and Advanced Hazard Detection concepts, the research team developed a virtual reality experience to immerse the stakeholders in future scenarios (Colombo et al. 2018).

This case study described a research project that represented an imaginary scenario through fictional solutions that would show how to use future technologies to benefit workers' health and safety. The scope was to let the industrial partner envision such possibilities, discuss them, and promote change within the company. The research teams used all sorts of different prototypes to develop such solutions. They had "Mockups" for physical objects and also "Props and Probes" (non-functional prototypes). Those terms had the same meaning to them. Therefore, they used one for another. These were useful in developing the design phase and communicating the idea to the other stakeholders. Also, they used physical objects (not called prototypes but "future tech samples") that represented the future technology, even though they it was not yet available on the market. For instance, if they were talking about "flexible sensors," they created an object (sample) that showed how they looked even if they did not work yet. They also made a lot of other supports (not called prototypes by them) that represented the technology of the future: videos, storytelling of scenarios of use, and posters with descriptions of the new objects and technologies embedded in them.

These artifacts with descriptive purposes helped communicate the scenario and elicit conversation to reach the general aim of the research.

As a last comment, Colombo said that presenting actual objects and proof of concepts of the future vision effectively enabled dialogue. Prototypes embed tacit knowledge, facilitate conversation, inspire, and communicate abstract contents, ideas, and potential applications in a concise, immediate and direct way. This kind of research and the creation of a system of prototypes proved particularly successful as the partner understood and appreciated the vision and decided to develop the research further.

Colombo pointed out one downside to this research approach. Such advanced storytelling—based on integrating physical, digital, and virtual prototypes—made future scenarios look very plausible. The partner could believe such solutions were ready to develop instead of just representing technology potential. So, an extra effort was necessary to remind the observer that the concepts were fictional and served as the first exploration of possible futures.

When the research team analysed the system of prototypes created throughout the project, they grouped them into two main aims. The first group combined all the physical and digital probes, mock-ups, storyboards, etc., used to create and develop new concepts. The second group of artifacts comprised look-alike physical and digital prototypes, descriptive videos, and virtual experiences to communicate the final results to all stakeholders.

The first group was more "speculative" than the second, but the whole case study (N1 in the interactive tool) was placed in the upper quadrants of our scheme since it had a speculative purpose (Fig. 6.1).

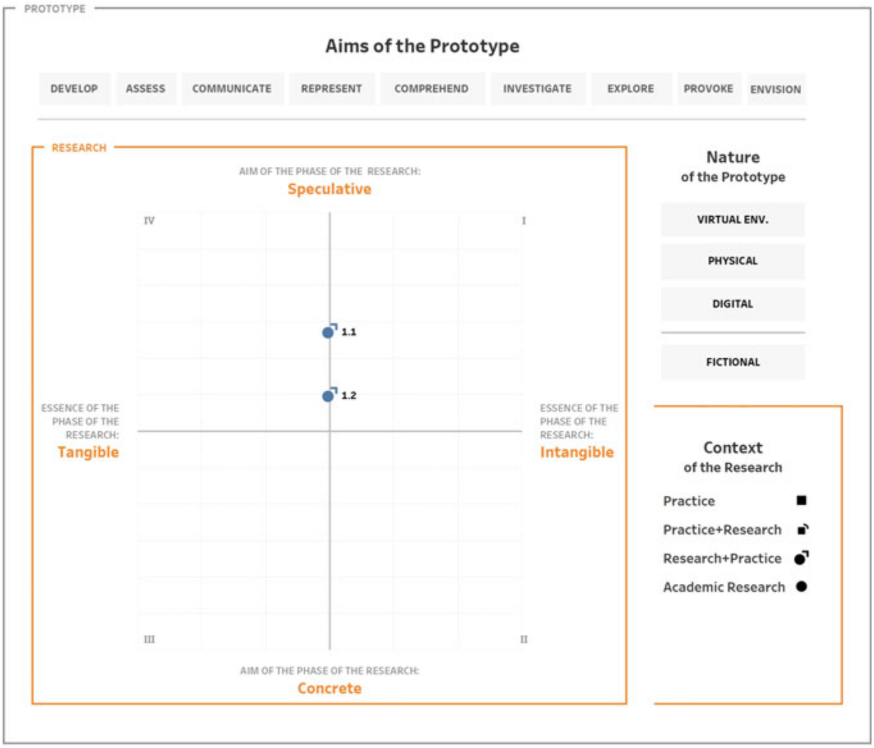

Fig. 6.1 Case Study "Augmented Health and Safety: Future Vision" displayed in the interaction tool

6.1.2 Exploring Technology Potential for User's Needs

We interviewed Stappers about his research experience at the Department of Industrial Design, TU Delft. As Sara Colombo, he identified his research context as across "research + practice" and "academic research".

Before dealing with the four Concepts (1. Transition, 2. Making theory, 3. Evolution and 4. Milieu), we discussed the meaning of the term "prototype" and our first attempt to find a definition. Stappers agreed that focusing on defining the term could be linguist research with little impact and usefulness for the design community. When compiling the review of Research Through Design, he found that many people talk about the prototype as something they make. This insight originated from industrial practice, where the prototype was the last before the mass production run started. Stappers thinks of that as a cognitive space where design results from multiple ideas and ends in a holistic concept, and then, when it gets materialized, it is called the "prototype." In the Human Computer Interaction discourse, which lately has become prominent in design, the term prototype refers to anything that is put together and has "the spirit of life in it." That is, if we are talking of a prototype of interactive systems, it would be something to interact with.

Stappers prefers to use the word "prototype" for precursors of material experience, but noticed that people also use the term "artifact" to refer to the same concept. So, he suggested we do not stick merely to the term prototype. Otherwise, we would miss several interesting insights in literature.

This talk confirmed that different interpretations of the term prototype belong to diverse communities. Indeed, in our understanding, within the design community, the central opposed interpretations regard the fact that a prototype should support a material experience, as suggested by Stappers, or it could support a visual experience, for instance, with videos and storytelling, as indicated by Colombo. As said before, we did not take a stand on the matter, we asked the interviewees to describe their case studies using all terms they commonly use, and we collected all of them.

Afterward, we asked Stappers' opinion on our theoretical findings starting from the first concept, "Transition." He answered that moving from abstract to concrete was the claim most often made of the designer's visualization skills. Designers can bring clarity by making the abstract visible. So, prototypes can have this function of making abstract concrete, and its benefits are similar to those found for visualization in enactments. Indeed, Stappers reflected that the transition from abstract to concrete also occurs in design areas such as service design, where prototyping is needed. In this case, it might make sense to say that when you enact a story to simulate a service, that is the prototype of the real thing you want to make later.

In our understanding, this transition well describes the general role of prototypes in design research, regardless of their materiality.

Moving to the second concept, "Making Theory" through prototyping, Stappers agreed, particularly with the idea presented in Chap. 1, that prototype(s) are proxies of theoretical instances to be tested. Therefore, they do not embody a to-be-developed product. Conversely, they display components of a potential product to be developed in an undefined future. Such parts are tested, contributing to the making of theory, and becoming elements to be grouped in diverse patterns valid for the design of possible future products.

He added a note on the term "tested," which usually means "validated." As in the Keller examples (Sect. 5.1.2.1), the prototype was used to explore the situation where the researcher had no hypothesis yet for discovery. Therefore, testing and discovery are two different parts of research, as a context of discovery and a context of validation. According to Stappers, these are two distinct functions a prototype can take.

As a reply to this note, we added that in our study, the prototype's *aims* that we collected were specific ones, like "I am using this prototype to test this function." In contrast, the prototype's *role* in the research was something with a broader meaning. In our way of saying it, if we go to the fundamentals of our understanding, the prototype might have a role of giving you knowledge about the product it is representing—so around the product itself—or of producing knowledge that goes beyond the product itself. While the first is more typical of industrial contexts, the second is more typical of academic contexts.

To this, Stappers added that in the chapter about Research Through Design, Giaccardi and Stappers (2017) wrote about this matter, saying that the goal of RTD is the production of knowledge. So, Stappers is one of the first scholars to endorse that a prototype can generate theoretical knowledge to be shared with others. Also, he noted that most literature about Research Through Design is about Ph.D. projects. Therefore, it is not surprising that they use prototypes for theorizing.

Speaking of the third concept, “Evolution,” we came up with some examples of other ways industries develop their ideas. Stappers mentioned the notion of the “concept car,” the model of a car that expresses the future direction of the company, usually also made to impress people. A concept car is not intended to be mass manufactured; it is designed to showcase ideas and let all the subcontractors know what direction the company is going. We commented that, similarly, it was common among furniture manufacturers to make small models of their furniture publish in magazines. Readers could not tell by the picture that they were miniatures, and companies could get feedback about them before fabrication. So, he concluded, prototypes can be used as an aspiration for the future, a way to make a theory, or a way to embody a new set of possibilities that were not possible until now.

Stappers narrated the case of one of his students who, after looking into concept cars, translated this way of working in the car industry into a consultancy practice for small and medium enterprises. For instance, he would do a two-day workshop for a chain of drugstore shops to explore the future directions and make a physical put-together playing-acting shop environment to show the customer journey through the shop. We, therefore, agreed that one of the top qualities of prototypes is that, while making ideas concrete, they leave out something from being complete; in other words, they have a certain *immaturity*.

About the last concept, “Milieu,” i.e., the influence on the context of the research activity, Stappers indicated it as a crucial point. The making of “prototypes” happened in the past and occurred in many other disciplines. Leonardo da Vinci, for instance, made several provocative designs that he did not use. Therefore, it is relevant for the design discipline to take a specific stance on this topic. In the end, he agreed that he also sees this phenomenon of academization taking place in design.

6.1.2.1 Case Study “Keller’s TRI and CABINET”

The case study Stappers proposed was the Ph.D. Thesis “For Inspiration Only. Designer Interaction with Informal Collections of Visual Material,” developed by Keller, supervised by him and Hennessey in 2005 (Stappers et al. 2014).

The research presents, on one side, the development of two prototypes, called “TRI Setup” and “Cabinet,” that were made to support designers in their work in the inspiration phase; on the other side, a thorough reflection of the role of these prototypes in the research itself.

The research’s starting point was observing the designer’s creative process and noticing that they collect visual material to look at for inspiration. These collections could comprise both digital and physical materials. This combination was crucial to the concept. So, the idea was to develop an interactive tool and an environment that would merge virtual reality's possibilities with traditional means used by designers to explore design concepts. During the doctoral research, two main prototypes were developed: TRI (Three Ranges of Interaction) Setup and the CABINET (Cabinet of curiosities).

The TRI Setup was a system for exploring design tools using various virtual reality techniques integrated into traditional tools. It was a body-scaled interactive medium supporting the designer, exploring design concepts by generating presence in an immersive environment. It was called TRI because it kept three levels of interaction (small, medium, and large). For the large scale, the researcher made an interactive setup to create the environment. He made a virtual and physical organization and presentation for the medium one. For the small scale, he provided a computer-supported sketching setup. The combination of the three ranges allows for an atmosphere fit to the assignment where designers can collaboratively discuss, arrange and visualize ideas (Keller 2005).

CABINET (Cabinet of curiosities) was an image collection tool that merges virtual and physical images into one seamless collection. It was developed with a user-centered approach where users were involved in the design process (Keller 2005). The exciting aspect of this design was that both prototypes could be experienced dynamically and interactively. So, they were actively used for research in a design process that was highly iterative, involving user studies, prototyping, testing, evaluating, and creating new prototypes (Sanders 2004).

As regards the role of prototypes in this doctoral research, said Keller (2005), the making of the projects was a means to both advance in the development of the design solution (Research for Design) and to reflect on the results and build shared knowledge (Research Through Design). This relation between theory and practice was based mainly on making working prototypes that could be experienced and that, through testing, could demonstrate and explore the premises of the thesis. So, the prototypes were designed according to a theoretical framework and let answers to the research questions. For instance, the Cabinet helped the author understand how designers interact with collections of visual material and what new tools can do to support this. The prototype made the implicit behavior of collecting explicit, either by invoking reflection on its users or logging the users' actions (Keller 2005).

During the interview, Stappers commented that Keller created a novel situation by prototyping a machine where a designer could have physical and digital images and work with them simultaneously. So, he could observe a phenomenon that nobody could observe before.[1] Stappers stressed the role of the prototype as a tool to explore and demonstrate the research questions.

When we analysed Keller's thesis, we clustered it into five groups of prototypes that roughly correspond to five specific aims we noticed. Firstly, we combined the several early prototypes made to research the theoretical framework of the thesis (dot

[1] This thesis was part of a collection of examples cited in the book chapter "The role of prototypes and frameworks for Structuring explorations by research through design and the RTD approach" (Stappers et al. 2014) that concretely describe what prototypes do in design research.

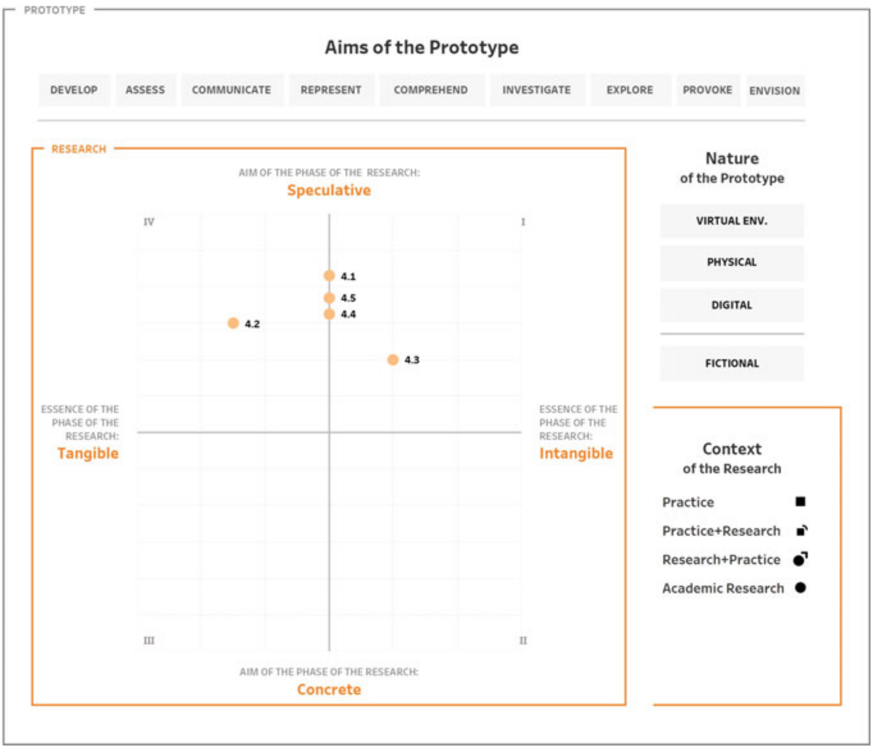

Fig. 6.2 Case Study "Keller's TRI and CABINET" displayed in the interaction tool

4.1 in Fig. 6.2). Since the topic was to use virtual reality to mix physical and digital image sources, the prototype's nature was also a mix of physical and digital features and virtual experience.

The second group (dot 4.2 in Fig. 6.2) refers to many demonstrations of Cabinet. In these demonstrations, several interaction styles and solutions were explored. So, these prototypes let the researcher finalize the concept and move forward in designing the final version.

A third one (dot 4.3 in Fig. 6.2) was the first technical prototype to see what possibilities such a repro camera combined with a digital camera could deliver. So, the prototype helped explore the image quality, speed, and interaction to assess and evaluate it.

In the fourth (dot 4.4 in Fig. 6.2) phase, we identified with the "The first working prototype of a collecting tool was called the Image Generation Station (IGS in short)." We understood that a working prototype lets the researcher integrate the different components that are especially important in a product that enables an interactive experience. Thanks to this understanding, we added "to integrate" to the original list of specific aims as part of the aim "develop."

Integrating electrical and digital components into physical ones represents blending the different competencies that come together to make interactive products.

In the evolution of the role of prototypes in design research, we noticed that "integrating" is crucial both if we speak of parts and components, as in this case, or integrating different artifacts into a system, as in Colombo's case study. Design is a discipline that coordinates other disciplinary knowledge to reach a purpose. The process of coming to life of this encounter/integration essentially takes place in prototyping.

The last (dot 4.5 in Fig. 6.2) is the final prototype. It is a working prototype that can be used to gain insights into how designers use collections of visual material in their design process and demonstrate how new media tools can support this. From this design process, the author took time to generalize his understating. This prototype was a research tool that helped gather knowledge about the new solution and the design process that such a working experiential prototype could support.

6.2 Prototypes for Industrial Design in Extra-Academic Research

6.2.1 Large Consultancy for an Industrial Partner

We interviewed two professional designers representing the design research that takes place outside the academic context.

Marco Meraviglia has over twenty years of experience, first as a designer for large manufacturing companies of domestic appliances and then as a project manager, expert in design and engineering, at Cefriel S.Cons.R.L. Milan. Cefriel is a digital innovation centre supporting companies in their growth through applied and experimental research. At Cefriel, they also collaborate with universities to develop basic research in digital innovation. Thus, it would be correct to place this in our context definition of "practice research."

We discussed our findings with Meraviglia. He noted that in his consultancy work, it is helpful to define from the beginning what they mean by "prototype" to ensure there are no misunderstandings with the client. Typically, the prototype is the final step of the process, the last object before production. They call it a "working prototype" as it embodies the final looks and functions of the product. He added that they do some partial working prototypes during the product development, with some functions to be tested. He said that outside of academia, the term also has a broad meaning that can change from context to context. Some use the word "mock-up" for what he means by "prototype," while he calls "mock-up" an object that is not working, it is a concretization of the concept but not a simulacrum of the final object.

On the other hand, sometimes, in the engineering development part, the "working prototype" does not have the shape of the products but the functions. It is an aggregation of elements that let understand the technical aspects. Sometimes, they might do both an aesthetic mockup and a technical working prototype. More commonly, thanks to the 3D printing possibilities that let make well-defined parts, they make more than one working prototype. They call them with an acronym that stands for progress: typically, WP1 has shells and some embedded parts and functions; WP2 is advanced with all features and functions, and so on. Finally, he agreed that he also encounters cases of things that are not as tangible to design as the interface of the smart objects for which they test the interaction. In their final working prototypes, they usually integrate the interaction features (even if the software might be a demo, not the final one). The interaction features may also be developed and prototyped aside from the product development and integrated into the working prototypes at the end of the process. At first, they might be slides showing the content of the interface; then, they could be presented on the screen of a computer. These also are called "prototypes" and let the object develop non-physical parts. At the company, Meraviglia works in the industrial design sector and thus focuses on tangible things, but other people in the design team work on interfaces, services, and experiences.

Discussing the evolution of design, we reckoned that in making intangible products, such as digital programs, it is possible nowadays to release "unfished products" that keep being updated after the release. From this perspective, it is difficult to say where the prototype ends and the final product starts. We wondered if something similar was happening with tangible products. Meraviglia noted that software is rented and who makes them is interested in keeping the clients by updating the product. You may review your product later and update it for a physical product, but it is not something that involves the client who bought the first version. With smart products, this is happening somehow since they integrate the physical body with embedded technology—electronic and software—that updates the digital features. We ended this discourse reflecting that since 3D printing became popular, we heard the idea of users repairing/updating their products by themselves. Probably, if products were something that the final user could complete/customize/repair/update to their liking, such objects would be "unfinished products," and the line between "prototype" and "finite product" would blur for the physical product too. So far, we reckoned this phenomenon did not take on because of several issues, such as safety and responsibility of any addition made by non-expert users.

Regarding "Making Theory", Meraviglia reflects on his past experiences working as a designer in large manufacturing companies. They would like the personal knowledge to be shared among all company members, but it is very complex. At Cefriel, sometimes they describe "best practices" to share and collect knowledge. Still, they are always for internal use. So, in their design research, the effort is not toward generalizing and sharing knowledge openly. Also, their clients usually do not want to publish such work. Thus, prototypes are not for making theory. They are made to progress in the design process and build knowledge about the product itself.

Regarding the concept of "Evolution," Meraviglia agrees with our reading of the phenomenon. He adds that the clients demand a working prototype as soon as possible because smart products require an interaction they would like to see quickly in the design process. So, they try to answer this request with partially working prototypes that let test and get feedback on at least some features. To make them, Cefriel relies on internal resources or suppliers. They can make internally simple paper/cardboard prototypes, motherboards, and virtual models for the augmented reality experience. While they will ask suppliers to do all the other parts. About the influence of 3D printing in the design process, he commented that one of the most impactful aspects is that it is possible to simulate an injected moulded part. saving a lot of money and time. It is an advantage for all the process stakeholders rather than the final user directly. While the possibility of making partial working prototypes through the design process, as said before, helps communicate with the client. It must be noted that expectations are high on the client side. Thus, it is better to agree beforehand on what such a prototype will be.

We also discuss that the clients must be educated about physical and virtual models and prototypes, as sometimes they are tricked by fidelity into thinking that the product is finished and ready for mass production.

Meraviglia concluded by sharing a thought he likes to repeat to his students—as he also teaches design engineering at the master level of Politecnico di Milano. He said that the engineering phase of a product development process is well done when the final product looks like the initial concept. In fact, when the idea concretizes into something manufacturable, some technical compromises might tackle the beauty of the original concept. So, the prototype is essential in supporting the designer to ensure this process is smooth and the result is equal to the expectation.

As regards the concept of "Milieu" he reflects on the fact that it is not a phenomenon he is aware of that much as it is not that visible outside of academic contexts.

6.2.1.1 Case Study "Hemomix MILANO"

For a case study, we selected an example of applied research: the development of a new device for blood collection monitoring called "Hemomix MILANO," awarded by the selection in the ADI Design Index 2021.

The tool monitored the safety and the steps of the donation. It had a scale function, weighing the collected blood, and a mixing function that avoids blood coagulation.

Cefriel held the research and development of the product for Delcon, an Italian company specialising in the ideation and production of medical devices targeting the U.S. market.

The device had many innovative features, beginning with the shape and layout that locates the interactive part higher toward the operator, avoiding fatigue and uncomfortable positions. Its structure was thought for frequent transportation in logistics that continuously relocate the devices to collect blood in different areas. The product could communicate remotely and has a touch graphical user interface to guide the operator in all the donation steps.

During the project's development, many prototypes were made alongside the design process steps. In Fig. 6.3 three types of prototypes are presented: low-fi cardboard rough model, concept high-fidelity shape mock-up, working and look-alike prototype.

Fig. 6.3 Low-fi cardboard rough model, concept high-fidelity shape mock-up, working and look-alike prototype of "Hemomix MILANO". Credits Cefriel

Consequently, we grouped the prototypes as follows. The first was a low-fi cardboard rough model (dot 2.1 in Fig. 6.3). It was done with recovered and scrap materials to evaluate and test the general dimensions and the overall layout during the first creative phase. Thus, it aimed at exploring the concept's main features.

The second (dot 2.2 in Fig. 6.4) was a concept high-fidelity shape mock-up (they also called "maquette") done with CNC machining and fine-grade finishing materials, with no authentic colours or appearance. It was meant to evaluate the perception of the volume and surfaces on a real scale and to address all human-related proportions and relations, especially the height of operation of the interface. It was used to show the overall idea and get feedback.

The third one (dot 4.3 in Fig. 6.4) was the Concept Virtual shape mock-up done at the same time as the previous one. It was an augmented reality 3D render visible via a Microsoft Hololens device; it showed the clients a look-alike version of the concept to appreciate surface materials, alert lights, display, etc. So, it was made to visualize the idea also regarding the interactive features.

The last group (dot 4.4 in Fig. 6.4) refers to three Working and look-alike prototypes, more and more refined. After the Concept validation and refinement phase, all iterations were made with working prototypes to test both functionalities and aesthetical design simultaneously. So, they were produced with SLS-printed plastic shells, press-bended metal parts, CNC machined metal and plastic details, and custom-designed electronic board prototypes. The functionality grade of the device increased from fundamental features to complete functionality among the three iterations, letting the team develop the final design up to engineering and production.

Reflecting on the aims these artifacts were made for, different aims were prominent at each stage of the process. At first, the main reason for developing the low-fi cardboard rough models was to "create" possible solutions that could address the design brief. Designers like to base their innovation on data and analysis and on a certain level of serendipity in the creative process. Such a rough model allows checking and experimenting with ideas at an early stage before proceeding further in development. In the second phase, the Hi-fi shape mock-up featured only the form of the device (not the functions) and aimed at showing the concept to the client and getting feedback. Parallel to this, the virtual model could represent the whole design and interaction to visualize the device's form and function. This technique is an advanced medium to experience new designs. Still, the designer told us that the quality of interaction was not "real" enough to make the use as valuable as foreseen. By the way, they expect these kinds of virtual experiences to develop further in the future and become effective in simulating the real interactive experience.

Finally, the three working and look-alike prototypes (dot 2.4 in Fig. 6.4) aimed to develop the device's form and function up to engineering and production. This aim fully matched the traditional definition of a prototype being the product's last version before production. Indeed, we notice that in a non-academic context, the terms they use are: "model" for the first rough and partial versions of the concept and "prototype" for the final working ones. Apparently, the traditional way of naming these artifacts persists outside academia. Yet, we noticed that what exactly is meant by "model" or "prototype" could change inside different companies' jargon. Therefore, a piece of good advice would be to not give for granted such meanings but clarify them to avoid misunderstanding. Indeed, Meraviglia said that clients expect to see working prototypes from the beginning of the process, and it is necessary to explain why several steps are needed before reaching such a level of refinement.

This Case Study represents how the traditional product development process is evolving. On the one hand, by anticipating some working prototypes during the process and on the other hand using new possibilities (the virtual experience) to predict interaction experiences. These insights confirm our reading of the phenomenon we described in the concept of "Evolution."

6.2.2 Small Studio in a Research Collaboration

The last interviewee was Gabriele Diamanti, cofounder of the Milanese design studio Ddpstudio. The studio works in different areas of design. Still, we selected it because they worked for the Prosthetic Center of INAIL (Istituto Nazionale Assicurazione Infortuni sul Lavoro) and the Italian Institute of Technology on developing a new multi-jointed prosthetic hand largely based on prototypes development.

We discussed the three theoretical concepts in the first part of the interview. As regards the first one, "Transition", Diamanti thinks that such a process of transition can change from one project to another at different levels. For instance, in his experience, the object that supports the transition is called a "study model," meaning a simple preliminary object made to test the first design ideas. In this case, the transition from an abstract concept to a concrete project is very elementary, and so is the mock-up/model (that Ddpstudio does not call "prototype"). It does not work or might not look good, but it allows crucial testing functionality for the project at the beginning

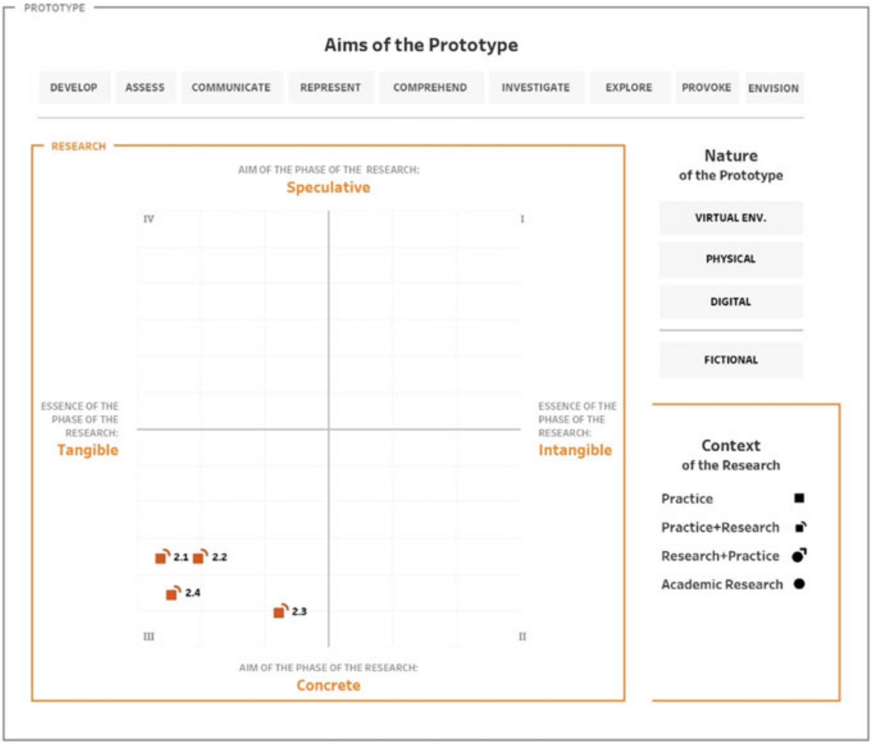

Fig. 6.4 Case Study "Hemomix MILANO" displayed in the interaction tool

of the process. For instance, in the case of the design of a rehabilitation platform, they made a 1:1 scale mock-up to verify right away a new adjustable foot attachment. This kind of preliminary mock-up is not aesthetic or has any other features but those necessary to test the attachment's mechanism. Diamanti also added that they usually do such "study models" internally to create and study their designs while they let their customers do the prototype to their specifications.

So, to recap, he agreed with the idea of transition but did not use the term "prototype" to name the first object made to enable it.

Talking about whether this transition should be tangible or not, he said that in his experience, the transition is more likely to be physical. However, he would not oppose using it to refer to intangible things. For instance, they once made a flowchart to explain an interaction design solution through a block diagram. So, they passed their abstract idea through a representation of it before making a physical product that would support such interaction.

As we said before, a debate is open on this matter. Some may say that such a representation is not a model or prototype. Nevertheless, we acknowledge this debate as it is without taking sides.

Regarding the second concept, “Making theory through prototyping,” Diamanti first replied that they do not document their design research process nor take the time to reflect and generalize what they have learned because it is not a priority. In their work with IIT, they are often involved in experiments with prototypes in the real world with real users. On such occasions, they do the reports (with videos and photos) to analyse the experiment outcome from the design point of view. The result is a document based on images and observations. Beyond these reports, they do not make any extra analysis to produce general sharable knowledge.

Regarding concept three, “Evolution,” and our reading of the phenomenon of the emergence of new prototypes and ways of prototyping, Diamanti does not agree completely. He agreed that, for instance, rapid prototyping helps to do parts that you could not do before, making the design process faster. As regards the fact that industrial products are getting “smarter” and require the integration of more expertise, he highlighted an obstacle. In his experience, the “smart part” complexifies the design and is not anticipated in the process. If a new solution is developed, the engineers do not simulate its behavior first. They build it and then test it. Thus, the available advanced manufacturing solutions, for instance, do not speed up this process. He commented: “Speeding it up doesn’t help that much.” Yet, we agreed that the role of the prototype is crucial in integrating all the inputs that make a smart product possible.

Regarding the last concept, “Milieu,” Diamanti does not have direct experience with the phenomenon, although he thinks it would be interesting to debate it.

6.2.2.1 Case Study “Hannes”

For the Case Study, Diamanti shared the design of Hannes, a new concept of a poly-articulated hand, able to restore over 90% of lost functionality in people with a limb amputation. Hannes is a device conceived and developed by the joint laboratory Rehab Technologies IIT—INAIL. The industrial design was curated by Lorenzo De Bartolomeis, Gabriele Diamanti and Filippo Poli—ddpstudio. The innovative aspects of the prosthetic hand regard both design and engineering aspects. On the design side, the main improvement is the naturalness of forms, movements, and orientation of the rotation axes and hand postures. Also, the anthropometric study has guided the prosthetic hand design, from the aesthetics to the mechanical and structural features, allowing the user to perceive the prosthesis, not like an external instrument but as an integral part of the body.

On the technical side, the differential mechanism at the base of the DAG system (Dynamic Adaptive Grasp) gives Hannes the peculiar ability to adapt to the object’s form and external stresses. Also, the control system is completely new. It implements traditional and new strategies based on artificial intelligence algorithms, which allow the user to control the prosthesis movements just by thinking of the movement they would do with their own limb. The customization of the functional parameters comes through a specifically designed software which is interfaced with the prosthetic hand through a Bluetooth connection.

The exciting aspect of this research is the collaboration of different experts throughout the process. On one side were the mechanical, electrical, electronic, and software engineers of the IIT. On the other, the designers of Ddpstudio and the medical experts and final users were actively involved in the research. The integration of input from these stakeholders took place around the prototypes and through an iterative design process that developed in the following main phases.

In the first part of the research, designers and engineers worked parallelly, developing prototypes for their specific research aims. The engineers developed two prototypes: the first (Fig. 6.5a) to test the mechanism and the second (Fig. 6.5b) to simplify the fingers and work on the wrist. These two prototypes were not applicable to users, so they were made to develop the mechanical aspects of the hand.

In the meantime, designers made several simple models (some paper, some 3D printed) developing the hand's shape and its rotation movements. This phase was based on a thorough study of the anthropometry and aesthetic of the actual hand. The aesthetic research for this project was based on observing the human body, gestures, and proportions. They also included a specific study of visual arts and sculpture history. Also, they studied the proportions of mannequins of the major fashion brands to have a reference to the current beauty canons.

So, the engineers and designers worked alongside for the first phase and achieved their specific research outcomes that later informed the progress of the joint research.

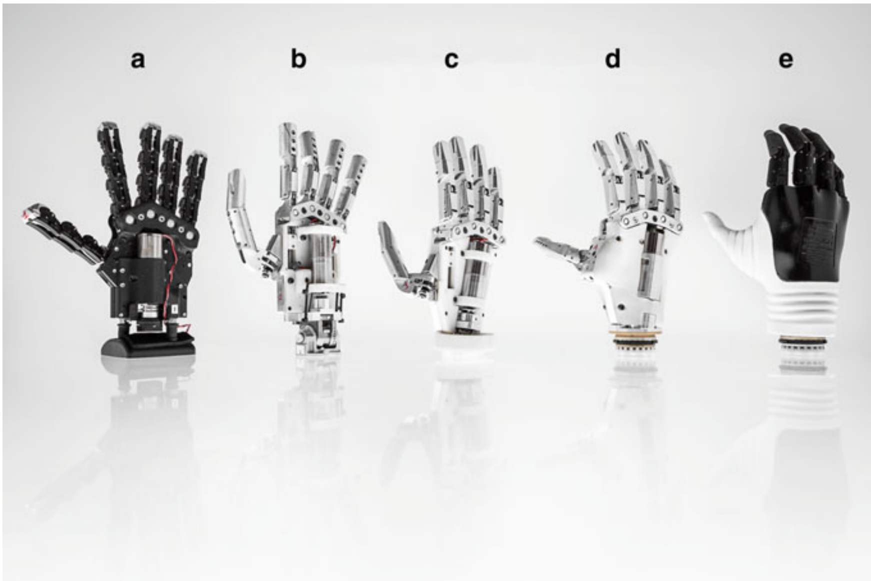

Fig. 6.5 **a**, **b** First engineering prototypes; **c** prototype integrating design and engineering; **d** prototype for first user test; **e** final prototype. Hannes credits joint laboratory Rehab Technologies IIT—INAIL and ddpstudio

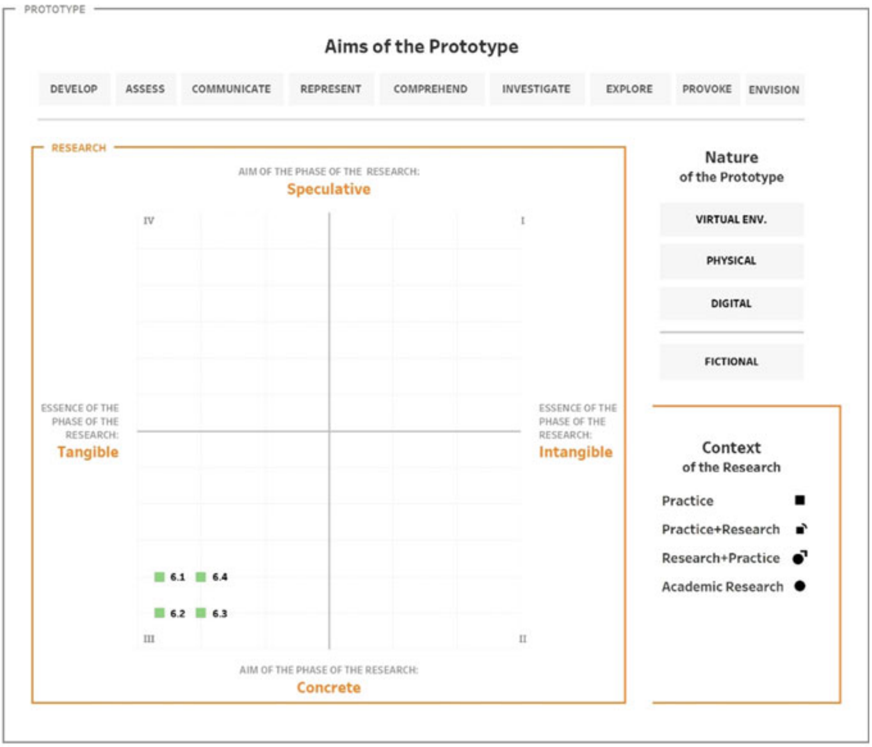

Fig. 6.6 Case Study "Hannes" displayed in the interactive tool

Anyway, as in this study, we are focusing on research in design; in the making of the interactive tool, we decided to represent—for this first phase—only the set of simple models made by the designers with the specific aim of creating the first concept of the hand (dot 6.1 in Fig. 6.6).

In the following phase, the integration of different disciplinary inputs took place. Thus, we used the specific aim of "integrate" associated with this phase and prototype (dot 6.2 in Fig. 6.6). The prototype (Fig. 6.5c) could not be placed on the user yet, but it integrated the engineering developments with the input from the designers.

In the fourth phase, the prototype (Fig. 6.5d) had two shells to protect the inner parts and made it possible to test it with the users. It was mainly used to get essential feedback from the users who could wear the hand and test its features. In this phase also, the clinic researchers are involved. So, we used the specific aim of "get feedback" associated with this phase and prototype (dot 6.3 in Fig. 6.6).

Between the development of prototype D and the E they reached an aesthetic shift that also brought an improvement in performance. Diamanti recalled that "it was in that moment that finally our requests to abandon the flat frame in favour of a "canopy" frame was heard. This new shape was the only way not to have the finger attachment points lying on the same plane. By putting them on different planes, we needed to achieve convergence of the fingers in the act of closing the hand. This was crucial for us to make not only the aesthetics more truthful but also the movement more natural. This was the fundamental step, which unlocked for us the possibility of reach the whole hand anthropometric at best".

The exciting aspect of this story is that the designer asked to move the motor from the axial position to gain a more natural shape and the unexpected result was that the efficiency of the mechanism improved too. Indeed Diamanti said "this step, by sheer serendipity, also brought a performance advantage because the routing of the cables inside the hand necessarily had to be modified, and the modification that brought the cable to run in two different planes made it more efficient and more mechanically advantageous".

The final working prototype (Fig. 6.5e) officially represents the outcome of the research: a structure that lets the finger converge in a natural gesture, a hidden smaller motor, and better performance and strength. The final prototype's high-quality results supported the winning of the Compasso d'Oro 2020, a prestigious Italian prize awarded by ADI (Associazione per il Disegno Industriale), and new funding to proceed with the development of the prosthetic hand. In the interactive tool, therefore, we associated this last prototype and phase with the specific aim of "embody," as it represents the ultimate stage of the materialization process to make the concept real.

This case study represents the integration and interpretation role of the prototype in a research project that combined highly technical innovation with the design's point of view and final users' collaboration (Ferraro et al. 2021).

6.3 Discussion

We noted some similarities and differences in the four Case Studies distributed in our interactive tool. Academic case studies are in the upper quadrants because they aim primarily at speculation. Interestingly, in the first case, the research aim was to explore possible future applications of yet-to-come technologies to support safe working conditions. So, although the research was for an industrial partner company, the general aim was more speculative than concrete. For this reason, the two main groups of prototypes and related phases go from a more speculative to a more concrete level but remain in the top quadrant of the scheme. They are placed in the middle of quadrants IV and I (tangible vs. intangible) because the system of products is a mix of physical and digital that supports an innovative interactive experience.

Similarly, Case Study "Keller's Tri and Cabinet" is in the top quadrants because, even if the research is based mainly on working experiential prototypes, the overall aim is speculative and supports the theoretical findings of a doctoral thesis. Placing the dots of this research is controversial in our understanding because each step had a practical aim to further develop the concept—as in a standard design process. Still, all steps helped reflect on the process and generate more general findings.

The dots represent a design process that goes from more to less speculative phases while concretizing the concepts until the end when a final reflective step occurs to finalize the general understanding of the whole research experience.

The two extra-academia Case Studies appear in the III quadrant as they represent the research process for making tangible objects within a concrete research aim. Indeed, they occupy the same part of the quadrant.

In Case Study “Hemomix MILANO”, the dots represent a minimal clockwise circular trend that goes toward concreteness, passing through dot 2.3, which represent the virtual prototype experience and thus is slightly less tangible. The last dot 2.4, is back to the left side of the quadrant representing the set of working prototypes, tangible physical, and concrete.

In Case Study “Hannes”, the dots represent a minimal clockwise circular trend that goes toward concreteness but ends with dot 6.4 at the same level of 6.1. indeed, the first set of prototypes had a more creative aim, the second and third (6.2, 6.3) were meant to proceed in making the prosthesis, and the final one (6.4) embodied the result aiming to communicate to all stakeholders its values.

To conclude, in these four Case Studies, we do not read trends we can assume as general rules, but we do see a general trend from speculative toward concrete aims of the research phases in which the prototype is used.

We must recall that we realized one crucial relation: the research phase and the prototype’s aim. In this scheme, any step in the research that did not have a prototype is not represented. Thus, the dots represent not the whole research process but only the related prototype. Also, some of the Case Studies represent research that developed forward (after our interview); thus, the trend of dots should probably continue to describe it fully.

The four interviews and cases gave us a vision of how design researchers use prototypes to develop physical and interactive systems, achieve speculation and theory and collaborate with companies and other research stakeholders. The research’s context and aim set the *specific* aims and nature for which prototypes are made. Integrating input from different expertise is a fundamental of prototypes as tangible products are more integrated with technology (mechanical, digital, electronic, etc.). The *working* prototypes are crucial for testing functions and interacting with users. While new ways of testing projects (i.e., virtual environments) are more commonly used, very simple moke-ups are still present; they are an irreplaceable way to support the ideation phase. In this perspective, in this area of design, prototypes are becoming more complex to support more complex objects, but they sum up to other simple models; they do not replace them. Even when collaborating with industrial partners, research might be called to support envisioning possible design solutions rather than producing them. Also, theoretical studies can be supported by tangible physical prototypes that let us create, communicate, integrate, and envision new ideas.

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Chapter 7
Final Considerations on Prototypes in Design Research

Silvia D. Ferraris

Abstract The study Paride presented in this book was developed by a team of researchers from the Department of Design of Politecnico di Milano. The aim was to have a general understanding of how the role of prototypes in design research is evolving. The investigation started with the literature review and analysis that let us frame a general overview of the matter, later examined through interviews with experts and a collection of case studies. We concluded that the general role of prototypes in design research is to support the transition from abstract concepts to defined design solutions. Prototypes can be used in specific phases of the research process to reach particular aims throughout the design research process. Prototypes are *purposeful* and *transient* objects made to concretize a conceptual idea. Playing these roles and reaching these aims, prototypes can support the generation of new knowledge—about and beyond the prototype itself—that can be translated into theoretical findings. These roles are evolving with the availability and integration of advanced technologies and the development of design discipline that is broadening and finalizing fields of research, methodology, and tools. The study had some limitations given to the time and extent of the investigation and other starting options on the approach. Nevertheless, during the research, we also came across some interesting extra insights, aside from the central topic of our discourse, that are worth mentioning and considering for further development.

7.1 Considerations from the Making of the Framework

Our study aimed to observe how prototypes are applied in design research to determine their role today. We assumed that the traditional role it played in the industrial manufacturing process—that of being "the first type of a mass-produced product" changed. Thus, we collected publications about prototype definitions (Blackwell 2015; Erlhoff and Marshall 2008; Geller et al. 2007) and prototype applications in

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design research (Valentine 2013), looking for insights from different design disciplinary areas allowing us to include inputs from other disciplines, such as engineering (Camburn et al. 2017; Moultrie 2015; Schrage 2013), where prototypes are used as well.

At first, we aimed to choose one definition of the prototype that would suit and guide our study, but we found it more interesting to leave this definition open. Indeed, we found out that *prototype* has different meanings among different disciplinary communities and even within a smaller context such as a single company. Furthermore, other terms—models, probs, artifacts, to mention a few—might have the same meaning of prototype in different contexts of use. Since we did not want to miss inputs, we collected any publication that would mention *prototypes* and similar terms aiming at having an encompassing overview (Houkes and Vermaas 2010; Koskinen et al. 2011; Gaver et al. 1999; Nimkulrat 2009). We embraced the indetermination of the data rather than trying to systematize it.

We started our study by collecting, reading, and analyzing the literature (Paré and Kitsiou 2017). We used two parallel approaches to it. On one side is a systematic collection of data, and on the other is the application of the Grounded Theory (Braun and Clarke 2006; Morse et al. 2009).

During the reading of publications, we found that the general contribution that prototypes could have in design research could be resumed in two primary roles. Traditionally, prototypes have brought ideas to life before manufacturing by testing a product's function, performance, and visual features. In this perspective, the prototype's role was to build knowledge *about the prototype itself* (i.e., function, performance, and looks). While today, prototypes are often used to generate new knowledge to reach an understanding at a higher general level that goes beyond the product under development, *beyond the prototype itself*.

Furthermore, we realised that every prototype is made to achieve a specific purpose throughout different phases of the design research process. After playing for such a purpose, prototypes might even be discharged. We collected all those specific aims and grouped them into nine main ones: develop, assess, communicate, comprehend, investigate, explore, provoke and envision.

Moreover, when reading the literature, we understood that beyond the general role of the prototype and specific aims, a set of categorization criteria (discipline, terminology, context, fidelity, and phase of the process) could frame the use of prototypes in the intention of the reference's author. We used these criteria to read and summarize all the publications, collect data in the case studies, and visualize them in our interactive tool.

After reading the literature and summarizing it in our Cards (see Sect. 2.1.3), we applied Grounded Theory Methodology to analyse it (Wolfswinkel et al. 2013). This bottom-up approach lets us understand the phenomenon summarised in four theoretical concepts.

Concept 1, "Transitions," referred to the understanding that the prototypes' role in design research is to support making embryonic ideas concrete through varied forms of representations and artefacts. Thus, enabling a *transition* from vagueness to clarity characterizes all views on the role of prototypes which dot the diverse landscape of design research. Various research areas understand and achieve the transition in different ways. We detected two opposite poles: on the one hand, speculative and intangible, and material and realistic on the other.

Concept 2, “Making Theory,” through prototyping, is the most significant aspect of an updated way of conceiving the role of prototypes in the field of design research, whether purely academic or practice-oriented. It implies prototyping to develop new theoretical knowledge. This vision is already shared in the design research community.

Concept 3, “Evolution,” referred to the fact that while traditionally, prototypes have been means to bring concepts of new products to life before manufacturing, today, they are going through a radical change, just like the design discipline is. The impact of embedded technology and advanced manufacturing processes, on one side, and the broadening of design discipline on the other, are at the base of this trend that involves the evolution of prototypes too.

Concept 4, “Milieu,” highlighted the fact that the role of the prototype has evolved hand in hand with the context in which it is applied. In this regard, the development of design, like an academic discipline, marked a fundamental step in the evolution of the prototype. The context in which the research takes place frames the role of the prototype more than any other criteria, determining the research purpose, methodology, phases, and, thus, all the specific aims for which prototypes will be applied in the process.

Overall, we can conclude that the general role of prototypes in design research is to support the transition from abstract concepts to defined design solutions.

Prototypes can be used in specific phases of the research process to reach particular aims throughout the design research process.

Prototypes are *purposeful* and *transient* objects made to move on in the process of concretizing a conceptual idea into a design solution.

They can support such transition in any design process, from purely speculative to practice-oriented studies. To do so, they can be of any nature—physical, realistic, intangible, or fictional—as long as they give an appropriate provisional form to the design ideas being developed.

Playing these roles and reaching these aims, prototypes can support the generation of new knowledge—about and beyond the prototype itself—that can be translated into theoretical findings (Stappers et al. 2014; Stappers and Giaccardi 2017; Mäkelä 2007; Niedderer 2013; Wakkary et al. 2015; Zimmerman et al. 2007).

These roles are evolving with the availability and integration of advanced technologies and the development of the design discipline that is broadening and finalizing fields of research, approaches, and tools (Bleecker 2009; Dunne and Raby 2013; Fraser and Seaton 2013; Kimbell and Bailey 2017; Kamrani and Nasr 2010). Also, the academization of design discipline is one phenomenon determining the role of prototypes in design research.

7.2 Considerations from the Application of the Framework

After reading and analyzing the literature and defining our framework, we shared it with experts. We collected their feedback on the theoretical concepts and a case study of their design research with prototypes. Meanwhile, we developed an interactive tool to help us visualize the relationships between the criteria describing the prototypes and the research they belong to.

In the tool, we made a research area divided into four quadrants that let us point out if the research was about something tangible or intangible (left and right quadrants) and if the research's general aim was speculative or concrete (top and bottom quadrants). Mapping the Case Studies, we noticed that doctoral theses are in the top part. The studies for industrial partners can be at the top or bottom, depending on whether the design proposal is fictional or realistic. Design consultancies tend to be in the bottom part even though nowadays they might develop fictional designs answering speculative questions, ending up in the top quadrants.

Many Case Studies are in the middle of the tangible and intangible areas because they represent research where the interactive feature of the design is predominant. This understanding generated some discussion (see Sect. 7.2.1).

The tool also showed the trends of the prototypes used in different phases of the research. In most Case Studies, all the research phases appear within the same quadrants and present a descending trend. Yet we noticed that in some Case Studies, there is the last phase where prototypes concur in communicating and discussing, thus ending up in a higher place in the tool's quadrants.

That reading confirms that, in general, the purpose of the prototype is to support the design process from abstractness to concreteness. Also, prototypes are used today for later final reflection and theorization phases.

We gathered a general agreement from all experts about the four theoretical concepts. Yet some interesting considerations arose during the interviews.

7.2.1 Tangible Transition or Not?

All experts agreed about the design process being described as a transition from abstractness to concreteness that prototypes concur to enable. When we asked if this transition should be through a material, tangible object, most experts said that, in their experiences, that would be the case. This consideration depends on the design area they belong to. As said, they all work in an area close to product design and interaction. Yet most of them also reflected that in other design fields, for instance Service Design (Blomkvist 2014), this transition could go through intangible means, such as experiences prototyped by visual tools or storytelling (Johnson 2011; Kirby 2010). So, they confirm our understanding that physicality is no longer a fundamental requisite for the prototype.

Also, some experts added that they might include in their design process: conceptual phases, where they use basic visual representations of their ideas (sketches, draft two and three-dimensional hand drawings or digital models, flowcharts, etc.), and communication phases, where they use storyboards, refined two and three-dimensional digital models, videos, etc. So, we agreed that those phases could be considered *intangible transitions* within the design of tangible objects. Yet we realized that examining the concept of physicality and intangibility in design today leads to further discussions, as in Sect. 7.2.2.

7.2.2 Are Visual Representation Tools Prototypes?

In literature, we could find several authors declaring or implying that representation tools belong to a different object category than prototypes (Hallgrimsson 2012; Lim et al. 2008; Pei et al. 2011; Yang and Epstein 2005). Indeed, this approach follows a more classical interpretation of design tools. Some objects visually represent concepts (like all drawings do), some let us interact with them (like models and probes do). The materiality of the object makes the essential difference in this categorization. In this reading, as the first ones are more passive and the second more interactive, they play different roles in the process. Visual objects are suitable for developing and communicating ideas, while physical objects can be tested, experimented on, experienced, etc. (Barati et al. 2017; Houde and Hill 1997).

This categorization is standard and appears reasonable but is put to the test by current phenomena.

Indeed, the fact that many products are now smart (Raff et al. 2020) means that it is necessary to use prototypes that anticipate the interaction in the design process. These objects might be paper prototypes, videos, simplified interactive applications, virtual representations of the product with simulated interactive features, and other things that imply an interaction. The interaction consists mainly of the user accessing visual information and operating manually (for instance, reading a screen and using buttons to select options). In this perspective, it is difficult, and perhaps pointless, to define whether this interaction is tangible or not.

Secondly, some experts commented that visual representations, such as storyboards, flowcharts, task analysis, mood boards, and other visual items, can be used to develop, share, anticipate, evaluate, investigate, and shape ideas of—for instance—interactions and experiences. In this perspective, the visual objects support achieving all the research phases, just like prototypes do. So, regarding the purposes, visual objects fulfill the same as prototypes. From this perspective, merging the categories (visual tools and prototypes) makes sense, as we did in our framework.

Furthermore, we witnessed the application of virtual experiences (Volino et al. 2015; Stjepanovič et al. 2017) in the design process to show clients the product to be. The development of virtual prototyping solutions started decades ago and is considered a promising solution to substitute many physical prototypes (Harms et al. 2009). Indeed, it is already so if we think the renderings, photomontages, videos, and all digital objects that replace physical versions applied in today's design process. So far, physical prototypes that support tangible interaction need to be real, not virtual. Yet, we are witnessing that in recent years the latest virtual systems are starting to be used—we saw that in three case studies—to let users experience the interaction with the new solution in a completely immersive virtual environment. The experts told us that those virtual experiences were not as efficient as they had hoped, but they commented that they expect them to advance and help anticipate and test their designs.

After all, categorizing *visual* or *tangible* objects is not as relevant. Categorizing into *passive* or *interactive* and *real* or *virtual* prototypes seems more relevant.

7.2.3 Fidelity, a Concept to Count On or Not?

When reading the literature, we came across several authors who referred to *fidelity* to describe prototypes (Hallgrimsson 2012; Lim et al. 2008; McElroy 2016). Fidelity defines how close the prototype is to the finished products. Most commonly, it refers to the look and feels aspects, but it can also refer to functions, performance, and interaction. Usually, it is qualified by the low–medium–high level to grade the approximation to the final object: from simple draft mock-ups to refined working prototypes. Very often, the fidelity level is associated with the design process phase. Two observations arose from the debate with the experts.

Firstly, we tend to imply that the first creative steps of the design process need low-fidelity models, and the final stages require high-fidelity ones. Stappers, let us reflect on this matter by sharing this interesting insight. Once, he was talking to Bill Buxton, an important engineer in the field of Human–Computer Interaction. On that occasion, Stappers told him how they used to teach the students to do low-fidelity prototypes and high-fidelity ones. Buxton objected that there is no such thing as low and high fidelity. "There is only fidelity that is appropriate and inappropriate to the purpose of the model or implementation" (Greenberg and Buxton 2007). Stappers said that he appreciated this insight. He agreed that if you tell students to do low-fidelity prototypes first and then high-fidelity ones, they might think they can do sloppy work initially and later do it with effort. While it means that the prototype you do at the beginning has different aims than the prototype you do after.

Secondly, all the stakeholders involved in the process should be educated about the concept of fidelity. Colombo told us that when they developed a vision of possible futures for the partner company, they made high-fidelity models integrated with interactive simulations in a virtual experience (Colombo et al. 2018). The final prototypes seemed very real, even if they simulated the use of technology not yet available on the market. Thus, they had to explain to the clients that their solutions looked real but were fictional. This issue should be tackled soon to avoid disappointment.

Similarly, Meraviglia told us that nowadays, clients expect working prototypes from the beginning of the design process, adding that working prototypes and well-refined digital models might trick clients into thinking the product is almost ready for manufacturing. So, he also stressed the point of educating the audience to avoid misunderstandings and create false expectations.

Thus, fidelity is a straightforward concept for designers that can lead to miscommunications if not appropriately used. We liked the suggestion to speak only of *appropriate* fidelity as it focuses on the aim: appropriate fidelity for the purpose of the prototype.

When interacting with other non-designers, emphasizing what the prototype is and represents is essential to reach a successful understanding and communication. This consideration will become more critical as real and fictional experiences mix, and all products' features will be realistically simulated in virtual environments.

7.3 Limits of the Study

The study was developed by a team of researchers from the same institution and the same disciplinary area of design (product and interaction design). A more varied team would have added at least some case studies in service and communication design, for instance, that would fill the II Quadrant of the interactive tool.

Then, during the research, we decided to have an encompassing approach and include all possible definitions of prototypes (or similar terms such as model, artefact, etc.) and any design research areas. The objective to achieve a broad view on the matter gave us a general understanding that might seem vague. A focus on specific disciplinary areas or contexts of research would reach a more precise definition of the prototypes and their role in such design research.

Also, after concluding the Paride study, we understood that we could pose some new questions to our experts. Indeed, we realized that the prototypes might have a marginal or central part in design research (and appear in just one phase or several phases of the process). So, in hindsight, we would also ask: "to what extent your research involves the use of prototypes?"

Furthermore, we realized that the definition of phases is relative to each research. Indeed, while the steps of product development product are quite consolidated among the design community, the phases of design research are not. So, we let the experts describe their case study's phases. We embraced this indetermination. As a result, the comparison among phases is not possible.

Eventually, while discussing the findings, we also realized that it is essential to consider the research level of development. In three cases, we found out that the expert shared a study that was later developed further. So, the general aim and use of prototypes could change. For instance, fictional research could be developed further to reach concrete results. On the contrary, a practice-oriented study could become part of speculative research, such as a doctoral thesis.

To conclude, in the discourse about the role prototypes in design research, it is necessary to consider the following:

- The disciplinary area and context of research.

- The extent of the usage of prototypes in the study.
- The level of development of the investigation.

The collection of Case Studies and their reading through the interactive tool did not let us generalize trends or rules because of the small number and the different results. Yet they helped us build a big picture of the phenomenon of prototypes' role in design research today.

7.4 Extra Considerations and Further Developments

During the research, we also came across some interesting extra insights that are worth mentioning as they widen the boundaries of our findings and could deserve additional investigation in the future.

7.4.1 When Does a Prototype Become a Finished Product?

Talking with the experts, we discussed the prototype definition, and some observations were raised, primarily referring to the traditional meaning of the prototype as the "first example of a new industrial product" as follows.

The example of Noronha is fascinating. Indeed, as said in Sect. 5.1.2 Noronha's objects are *unstable* because they can be seen differently depending on the context: they can be seen as medical prototypes, sculptures, or design products. They tell a story and can be exhibited in a gallery or a museum, and they can be taken either as finished objects or prototypes. Eventually, Noronha calls them *artefacts*. Indeed, those objects were sold to clients as *limited-edition artefacts*. Thus, they had a value and a market as art pieces for what they represented, while they also have been part of design research crossing the boundaries of medicine. In this case, an object can be simultaneously a finished product—a piece of art, a sculpture specifically—and a prototype of a prosthesis in speculative design research. This phenomenon, we reckon, can happen in design, a discipline traditionally close to art, and above all, it can happen to prototypes that are, as we said, purposeful *transient* objects, ready to change into something else or cease to exist.

Secondly, we discussed that digital products today, like programs, apps, etc., can be released on the market and updated when they are in the final users' hands. The user buys a finished product that keeps evolving. The updates are meant to improve the product. We wondered if those digital products are "finished" or "refined prototypes" that keep evolving over time. Although we could not find an answer to this, we reckon it is an interesting thought, mainly if we translate this concept to physical objects. In the past, industrial products were sold as "finished," but today, smart products can be updated by the manufacturer after the purchase. So, at least partially, this "unfinished" feature is entering the physical world. This idea had already developed partially following the spreading of digital printing when maker movements and DIY enthusiasts imagined a future where physical products are self-made, customised, and repaired. We will see if this marginal approach will reach a mass market with products that can be updated, like the software. It could be good news for sustainability. We thought this could be an interesting matter to investigate further.

Referring to the discourse of virtual products, environments, and experiences, we also discussed the possibility that designers might design virtual products for the virtual market, such as the *metaverso*. This phenomenon already happens in the industry of games, where players can buy costumes, weapons, and all sorts of gadgets for their figures. These virtual objects can be updated without effort but with a cost. In this perspective, designers would make products that will never have to stand the proof of becoming real, will be constantly improvable, and thus, be potentially *transient* forever.

These discussion topics depend on the boundaries of design disciplines, traditionally close to technological and artistic areas but also open to crossing new ones and merging with others. They represent areas of future development for design prototypes.

7.4.2 Always Make Use of Prototypes or Not?

We came across another interesting topic of discussion that would need further investigation. Most of the interviewed experts pointed out the necessity of prototyping as a design research method. That is not a surprise since we chose them for their research approach, which implied the use of prototypes. But some stressed this point. For instance, Ayala-García said, "it is mandatory to use prototyping as a tool. Not a tool to refine ideas, but a tool to construct ideas. It is, in my opinion, one of the "secret tools" of the discipline" (Sect. 4.1.2). Indeed, we reckon that most authors in the literature consider prototyping an essential methodology of the design process. Prototypes are part of the design DNA. Yet, Kerspern's alert caught our attention. He said that in some academic and professional contexts, designers make prototypes because they are taught and expected to. They might do it blindly and superficially because it is part of the design process. This vision seems to contradict our definition of the prototype being *purposeful* objects. True is that the research's purpose sets the prototype's purpose. Making prototypes might not be valuable if not part of a worthwhile project. Design and researchers should take the time to set the research's objective, methodology, phases, and tools. The prototype should be a meaningful act of meaningful research.

7.5 Final Recap

Overall, we concluded that:

- The general role of prototypes in design research is to support the transition from abstract concepts to defined design solutions.
- Prototypes can support such transition in any design process, from purely speculative to practice-oriented studies.
- Prototypes can be of any nature—physical, realistic, intangible, or fictional—as long as they give an appropriate provisional form to the design ideas being developed.
- A set of criteria can describe prototypes and their use in design research. Among such criteria, the *aim* is the most important.
- Prototypes can support the generation of new knowledge—*about* and *beyond* the prototype itself—that can be translated into theoretical findings.
- These roles are evolving with the availability and integration of advanced technologies and the development of the design discipline that is broadening and finalizing fields of research, approaches, and tools.

We started our research understanding that it was worthless to look for an encompassing definition of prototypes that would apply to all disciplinary fields and converge all meanings. Thus, we accepted that due to the term prototype's open meaning, our investigation's boundaries were fuzzy. Nevertheless, we ended up finding one that at least applies to the design field:

> In design, prototypes are *intentional* and *transient* objects made to concretize a conceptual idea.

Furthermore, we shared other considerations on prototypes in design research.

In the design community, it is accepted that the transition from abstract to concrete enabled by prototypes can be by tangible and intangible means.

When interacting with other non-designers, emphasizing what the prototype is and represents is essential to reach a successful understanding and communication.

Making prototypes might not be a valuable activity in itself. It is always the research's purpose that sets the prototype's purpose. In other words, the prototype can play a meaningful role in meaningful research.

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