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Hansen, Camilla Arndt; Ozkil, Ali Gurcan

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From Idea to Production: A Retrospective and Longitudinal Case Study of Prototypes and Prototyping Strategies

Camilla Arndt Hansen

Department of Mechanical Engineering,
Technical University of Denmark,
Nils Koppels Allé,
Bygning 404, rum 229,
2800 Kgs. Lyngby
e-mail: cahan@mek.dtu.dk

Ali Gürcan Özkil

Department of Mechanical Engineering,
Technical University of Denmark,
Nils Koppels Allé,
Bygning 404, rum 232,
2800 Kgs. Lyngby
e-mail: alio@dtu.dk

ABSTRACT

This study explores the value of visualizing the prototyping activities in a new product development process from idea to production. Through a case study of a hardware startup, we present a retrospective and longitudinal study of their prototyping processes, from early idea to the introduction of several product generations to market. We call the visualization technique ProtoMapping and we use the qualitative and quantitative data captured by the ProtoMap to understand how prototyping strategies change over the course of product development processes. Specifically, we focus on the prototyping of

parallel concepts, iterations of concepts, manufacturing processes used for prototypes, prototype media, prototype tests, as well as prototyping of isolated or integrated systems. Based on this longitudinal analysis, we present a number of insights that were possible to uncover with ProtoMapping. We observe how parallel prototypes of isolated systems can be used to explore the solution space and later be synthesized into prototypes for integrated systems. Furthermore, we understand how the need to scale up production can lead to increased prototyping activities, as several parts of a product must be redesigned. This study illustrates the utility of a retrospective visualization approach and serves as the first step in formulation of generalized guidelines for prototyping strategies in holistic product development.

INTRODUCTION

Prototype early and often. This is the advice from several studies explaining how prototyping in the early stages of hardware development can help to explore new ideas [1], reduce uncertainties [2], increase feasibility [3] and engage with users [4, 5]. Prototyping has long been recognized as an essential part of new product development [2, 5], but in recent years there has been an important shift in the understanding of when and how to prototype.

Traditional linear design processes may show 'prototyping' as a single, separate phase in the later part of the development process – a validation of a design before a product is produced and released to market [6, 7]. However, adaption of the agile frameworks in hardware development [7, 8] as well as new methodologies such as the Design Sprint [8] and Lean Startup [9] has led to circular and iterative representations of the design process. Prototyping can no longer be defined as a single phase in a linear process; it is a continuous and iterative activity covering the entire progression from idea to production [8, 11].

Recent years witnessed a growing body of literature discussing how to prototype effectively and efficiently [1, 11]; how to reduce cost and fabrication time while prototyping [12] and how prototype fidelity can influence the perceived risk of a concept [13]. While these works provide a better understanding of prototypes and prototyping activities, most of them focus on narrow timeframes within the early and explorative phases of product development and report on building prototypes at a single point in time.

Prototypes fulfill many roles in companies and startups, but prototyping activities are not planned using structured methods [14] and the knowledge generated through prototypes are not managed or documented systematically [15]. There is still a need for a more holistic understanding of prototyping strategies in relation to the product development and realization [16]; how prototyping activities change over the course of the product development and how early-phase prototypes may affect the prototypes made later in the process. Understanding these relationships can allow us to contextualize current prototyping strategies so they fit the varying stages of new product development.

Overall, we need to learn more about how prototypes are used in practice [1, 11], but we rarely have the opportunity to observe prototyping activities in the context of a product development process. We argue that there is a strong need for a systematic approach for the documentation and management of knowledge for hardware prototyping. This would allow us to understand the existing practices and to be able to assist practitioners with their prototyping strategies.

Research Aim

New insights about prototyping can be gained by visualizing the prototyping activities in product development processes. A prototype is a materialization of the questions, hypotheses, knowledge and ideas at a given time in the development process for a product. By mapping these variables against each other in a structured way, we expect to be able to identify relationships between prototypes and prototyping activities, observe when they change over time, and understand how they influence the final product.

The objectives for this paper are two-folds: (1) to provide a template for the structured visualization of the prototyping processes in a hardware startup and (2) to exemplify the value and potential uses of this visualization by presenting the learnings from the case. This leads to the overall research question: *Which new insights can be gained by analyzing a visualization of the prototypes in a product development process?* The open-ended exploration of insights derived from such a visualization is guided by following sub-questions:

- *RQ1.1: How do prototyping strategies change from early phases to later phases of development?*
- *RQ1.2: How does prototyping affect product realization?*

Our case study is based on the product development data that has been accumulated by the hardware startup 'PeeFence' over the past six years. From the sketches of early ideas to a product on the market, PeeFence has accumulated various

types of data on their product development activities. This paper utilizes this data to visualize the entire product development process of PeeFence through their prototyping activities and uncovers how prototyping strategies are affected by different contextual factors.

Contextual Prototyping Strategies

When designers decide to build a prototype, they are confronted with a number of options for the embodiment of the prototype. Christie et al. [16] define a prototyping strategy as “the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)”. In the same paper, the authors present nine factors to consider in terms of embodiment: (1) prototype a sub-system (isolated system) or an entire system (integrated system), (2) prototype multiple parallel concepts or a single concept, (3) iterative prototypes or 1 prototype per concept, (4) virtual or physical prototype, (5) outsourced or in-house prototype manufacturing, (6) physically scaled prototype, (7) functionally scaled prototype, (8) prototype of similar or different material than the final design, (9) similar or different manufacturing technique than the final design. Camburn et al. include these in their list of strategic decisions and add additional factors, such as the decisions on how to test prototypes [18].

The recent work in prototyping strategies stem from the fact that practitioners not always make a deliberate strategy for their prototyping activities [12]. The lack of a prototyping strategy can ultimately result in the failure of the project [16], whereas the proper use of prototyping strategies have shown improved performances of the final

design and a reduction of resources spent on prototyping [12, 17]. Therefore, several methods and frameworks have been proposed to assist designers in determining a suitable strategy for their prototyping [1, 12, 13, 17]. While these take different contextual factors into account, such as experience level and time constraints [18], they do not consider how strategies need to change over the course of the product development process.

Timing in the process is considered to be defining for the selection of strategies [1, 6, 17]. Yet, we find limited guidance on how to prototype depending on timing. For instance, Tiong et al. present 10 prototyping heuristics, in which two principles consider timing broadly, stating “prototype for functionality early” and “integrate subsystems early” [11]. Similarly, Yang investigates whether the timing of prototyping activities in the design cycle can be associated with certain outcomes and finds that spending more time on prototyping in the early phases of a design process leads to better design outcomes [21]. Prototypes have also been defined by their purpose in the design process. Ullman describes how prototypes evolve from a proof of concept, to a proof of product, a proof of process, and finally a proof of production over the development process [22], while Ilg, Wuttke and Siefert illustrate which types of prototypes are suitable in the different phases of a product service system design process [23]. These are beginning efforts that need to be expanded and synthesized with the goal of providing actionable guidelines on the use of prototyping strategies in the context of a development process.

Visualized Prototyping Processes

In the engineering design literature, we find two dominant ways for visualizing prototyping processes: (1) Visual models that present generalized or abstract representations of the prototyping process(es), and (2) data visualization projects that map data gathered from real development projects in a structured way.

Some models illustrate the steps in a single prototyping activity, such as Thomke's experimentation framework that presents prototyping as a four-step iterative cycle [19]. Such representations visualize detailed aspects of a prototyping activity, but often exclude the relationship between the many prototyping processes that are carried out over an entire design process. If we instead look at the product development process as a whole, we find a great number development models, such as the well-known VDI 2221 for the systematic design of technical systems and products [24], or data visualizations, such as Seow et al.'s structural mapping of design innovation processes from four case studies [25]. Prototypes and prototyping may or may not be included as an activity, a phase or an outcome in these models. Regardless, these illustrations often have a high level of abstraction, making them too general to illustrate the prototyping processes in detail.

We find a limited number of visualizations that provide details on a chain of prototyping activities. For instance, Camburn et al. [13, 20] use six of the previously presented prototyping strategies to model a "prototyping strategy space" with multiple parallel concepts and multiple iterations of each concept expanding the space (Figure 1). Böhmer et al. present a similar structure for a prototyping roadmap, visualizing

horizontal prototypes (testing different features) and vertical prototypes (increasing the level of detail for a feature) as part of agile hardware development [6]. In another study, Camburn et al. explores the use of topological vectors and wireframes to visualize search strategies for complex products, services or systems [26]. Menold, Jablokow and Simpson connect their 'Prototype for X' framework to the development process by showing how a prototyping activity can inform each development phase [10]. While the mentioned models show detailed aspects of the prototyping activities, there is no indication of how these change from the beginning of a project to the end.

In connection to the need for contextual prototyping strategies, we need to expand our understanding of how prototyping processes are structured at the level of abstraction that make it possible to observe prototyping processes in detail, for more than a single activity at a time.

The study presented in this paper takes its departure from the above-mentioned guidelines, tools and methods to create a visualization tool to analyze product development processes from a prototype-centric viewpoint. It differs from the existing work in three ways: First, it pivots on a complete and longitudinal case study that spans over entire product development process. Second, it provides a formalized approach to visualize multiple prototyping activities, and third, it provides the identification of prototyping strategies regardless of whether the designers have made deliberate strategic decisions or not.

METHODOLOGY

To answer the presented research questions, we follow the research methodology illustrated in Figure 2. The research is initiated with the collection of product development data accumulated by the hardware startup 'PeeFence' over the last six years. The prototyping processes are visualized in an explorative process that seeks to structure the extracted data using the existing theoretical background in prototyping strategies.

During the data analysis, both quantitative and qualitative parameters are considered to identify and characterize the prototyping strategies. The data visualization and analysis have an iterative nature, as the initial analysis guides the understanding of what and how to visualize PeeFence's prototyping process. The result is the final visualization – a ProtoMap - illustrating PeeFence's prototyping journey and a number of graphs presenting the change in prototyping strategies over time. Insights from the analysis are presented and discussed to answer the research questions. Finally, the perceived value for practitioners is evaluated with a questionnaire and follow-up interview with the case company.

Case Study of PeeFence

PeeFence is a hardware startup, which produces lightweight urinals (also called PeeFence) that are installed on the fences at festivals, street events, construction sites, and similar settings. PeeFence consists of a piece of plastic sheet that is fastened to fences with strips and rolled up in the bottom to form a trough to collect and lead away

the urine. The idea originated in 2013 through a collaboration between Denmark's largest festival Roskilde Festival and the Technical University of Denmark, where PeeFence's five founders studied at the time.

Since 2013, PeeFence has evolved from an idea to a proven product with several generations. We have named the different product generations in Figure 3, using product version numbers (V1.0, V1.1 etc.) from the first point in time where PeeFence was paid by a customer. During the first four years, the PeeFence founders worked part time and the development efforts were focused around the months leading up to Roskilde Festival. However, from 2017-2019 two of the founders worked fulltime in the company, which led to a growing customer base and the development of PeeFence V2.0 that is designed for direct sales rather than serviced rentals.

Similar to other hardware startups, PeeFence has centered their development process around prototypes [15]. While they have documented their prototyping activities in a fairly structured way (especially through the use of pictures and videos), they have not made deliberate decisions in terms of using defined and structured prototyping strategies.

There are two main reasons for choosing PeeFence as a suitable case for the visualization of prototyping processes. First, they have gone through many iterations of their products, from early ideas to scaled production, which provides data to analyze the longitudinal aspects of prototyping. Second, due to the fully mechanical nature of their product and the data that is collected, most of the changes in prototypes and product versions can be visually observed and assessed.

Product Documentation and Data Collection

The purpose of the data collection is to identify the prototypes made by the case company from the beginning of concept development in 2013 until 2018. The prototypes were identified in three stages.

First, an overview of the prototyping activities were obtained through an in-depth interview with one of the founders. The interview was structured as a chronological investigation of the case company's product development process. Together, the founder and the authors drew up a rough timeline of the case company's development process including product versions, main prototypes, the knowledge gathered from prototyping activities and other contextual factors influencing the prototyping processes.

Subsequently, the case company's collection of data and documentation was analyzed to identify the prototypes made during the different phases of development. The investigated data consists of 1243 pictures, 17 videos, 87 CAD files, 58 technical drawings, 3 reports, 23 work sheets, 67 meeting notes, and 13 stakeholder presentations. The overall timeline was split into six branches for the development of each of the six product generations. Assessing the time-stamped documentation allowed us to identify and add individual prototyping activities to the respective timelines. The focus at this stage was to extract and capture the relevant prototyping data, while the question of how to structure and visualize the data for analysis was saved for later.

Lastly, a follow-up interview with the founder ensured that the prototypes had been identified correctly and no development steps had been overlooked. From this interview, the accuracy of the developed timelines was validated and additional detail collected on the motivations behind changes made to the product design.

Developing the Visualization Method: ProtoMapping

The main motivation for the development of the visualization is to organize the identified prototypes in a way that enables us to compare prototyping strategies in different parts of the product development processes. This is made possible by building the visualization from three layers of information: (1) the prototyping processes, (2) the utilized prototyping strategies, and (3) the flow of information across versions and generations that illustrate the contextual factors and connections across different prototypes. The following sections present the steps taken to build the visualization that is used for the analysis, structured as seen in Figure 4. We call this visualization technique ProtoMapping and the final visual a ProtoMap.

General Structure of the Prototyping Processes

Our visualization approach takes its departure from Camburn et.al.'s conceptual model [20], shown in Figure 1. This model is selected as its basic structure allows for the mapping of prototypes over time, while maintaining a level of flexibility that enables it to contain the unique prototyping processes from several different types of projects. Thus, the prototypes identified in our case study are illustrated either as a part of the

iterations (organized horizontally) or as explorations of parallel concepts (organized vertically).

A challenge arises, as the relationship between iterations and parallel concepts is more complex than the existing prototyping strategy map can illustrate. The case company explored many parallel concepts on a sub-functional level and later synthesized some of these into integrated concepts. These sub-functional level prototypes can be considered both as iterations of integrated concepts as well as concepts being explored in parallel. The model presented in Figure 1 provides a high-level conceptual understanding, but in order to capture the complexity of a real-life case study we have expanded the model to represent the transformation of *Functions* and *Means* that makes up the product [27]. Like the hierarchical structure of a *Function-Means Tree* [27], our model illustrates how an overall integrated concept is realized through a number of functions and how each of these functions can be fulfilled through a number of alternative isolated concepts. As shown in Figure 4, our model distinguishes the concepts for integrated systems and the concepts for isolated systems in separate axes.

Prototyping tests - explicit points of evaluation during the development process - are also added to the model to further analyze the outcomes from prototyping activities. Prototypes are commonly defined by their ability to be tested to answer a specific question [20, 28]. Using this definition, we expect an equal number of prototypes and prototype tests. For simplicity, we have only included the prototype

tests that go beyond internal evaluation of a design within the design team, e.g. testing with external elements (e.g. a fence) or with external stakeholders.

Similar to the consideration of prototype tests, the visualization process demands constant evaluation of the level of abstraction and the definitions to use during the analysis. In order to reach a meaningful representation of the case company's prototyping processes we make the following assumptions:

- 'Prototypes' are defined broadly, and they refer to any representation of the design. However, for isolated systems only sketches transformed into virtual or physical models are considered prototypes.
- A new iteration is defined as a change of media (e.g. a change from CAD model to physical model).

Identifying Prototyping Strategies

Next, we seek to identify the prototyping strategies that were utilized in the development. Through an initial analysis of the data, we have identified the use of several strategic factors, and selected a subset that is relevant to answer our research questions. The strategic factors analyzed in our model are presented in Table 1. The characteristics for each prototype or prototype test is indicated on the ProtoMap as seen on Figure 4.

The three strategic factors *prototype media*, *manufacturing technique*, and *prototype test* are visualized as an attribute for each individual prototype or prototype test. The other three strategic factors, *parallel concepts*, *iterations*, and *system level* are

already illustrated through the visualization structure that exists when the identified prototypes are organized as previously described. These factors cannot be identified through the analysis of single prototypes. They materialize from the ProtoMapping process, as our view on prototypes transforms from an observation of 'artifacts' to an observation of 'processes'.

Information Flow across Prototypes

The final layer of information added to the visualization model is the flow of information and data across prototyping activities. We emphasize the learnings that were acquired from prototyping and how they were used as input for subsequent prototyping processes. These provide context for the prototyping activities and illustrate how the outcomes from different prototyping activities affect the rest of the development process.

Analyzing the Visualization

The ProtoMap allows us to observe the use of prototyping strategies in the development process. In this study, we are guided by the research questions to focus on the change of prototyping strategies and how prototyping affects product realization. Both quantitative and qualitative insights are needed to answer these questions, as the quantitative data allows us to identify when and how often a prototyping strategy was used, while the qualitative aspects help us understand why it was used and what the consequences were.

The qualitative analysis uses the developed visualization structure to uncover the case company's prototyping story as a whole. We also identify cases of interest where particular strategies were used, how and why they were chosen and how they affected the final product.

Quantitatively, we analyze the frequency of different strategic decisions. From the developed ProtoMap, we are able to trace the occurrences for each strategic factor. This allows us to compare the use of the investigated prototyping strategies over each product cycle.

Evaluating the Visualization

Finally, we presented the ProtoMap and our insights to the case company and conducted an evaluation interview to understand the perceived value of the results from the viewpoint of the practitioners. The evaluation was carried out using a questionnaire and a subsequent interview with one of the founders of the case company. The answers from the questionnaire were used to inform the follow-up interview, investigating the reasons behind the answers and how to increase value in the future.

RESULTS

The main results from the data visualization and analysis are the ProtoMap showing PeeFence's prototyping processes (Figure 5) and a number of associated graphs

that illustrate the change in popularity of the different prototyping strategies over the six developed product generations (Figures 6-11).

The ProtoMap

The ProtoMap in Figure 5 provides a coherent picture of a product development process over various generations of a product. We can describe PeeFence's development as an iterative process spanning six product cycles, with an average of 19 prototypes in each cycle. Figure 3 illustrates the evolution of the product and even though all of the versions look visually similar, our analysis uncovers that there are substantial differences in terms of functionalities and product characteristics that affect transportation, installation and scale of production.

The ProtoMap reveals an example of an agile hardware development approach inspired by recent methodologies such as LEAN Startup [9], Design sprints [8], and Scrum [32]. These approaches all advocate development over several iterative cycles, where integrated prototypes are made to test and learn at several points during the development process. The integration points makes it difficult to distinguish between 'product' and 'prototype' in PeeFence's development process, which the founders did not do either. If a solution worked, then what was before a prototype may have been part of the products delivered to the customer. Their overall strategy can therefore also be described as evolutionary prototyping, consisting of a number of cycles that each improve the product over time [31].

PeeFence has explored five holistic concepts in parallel – two in the beginning of the process and three new concepts at a late stage in the project. The prototypes below the horizontal axis represent eight sub-functions¹ - parts and entities that must be combined to provide the full functionality of a PeeFence: (1) mounting on fence, (2) roll up of the trough, (3) drainage, (4) material, (5) dimensions, (6) print, (7) assembly of funnel and trough, and (8) assembly of funnel and hose.

The ProtoMap in Figure 5 communicates the story of PeeFence's development process through its prototypes. It is possible to read and understand the prototyping story without watching the ProtoMap, but it has emerged from the ProtoMapping process and would not have been uncovered in this detail without it. Below, we present a brief version of their story, which provides the basis for answering the research questions during the Discussion. In the text, we refer to areas of interest (**#**), marked on the ProtoMap.

Cycle 1: Alpha prototype

(1) PeeFence initiated their product development with two parallel concepts for fence-installed urinals. **(2)** They did not prototype these concepts at an integrated level before selecting one concept, which was split into six sub-functions. **(3)** Between two and four sub-concepts were prototyped for each of the sub-functions in isolation, using CAD models and 3D printing for the majority of prototypes. Simple functional tests determined which sub-solutions were selected for the integrated Alpha prototype. **(4)**

¹ We realize that some of these are not actual functions. However, as we wish to illustrate PeeFence's prototyping process accurately, we have applied their decomposition and definitions in the visualization.

The single Alpha prototype was installed at Roskilde festival during the festival week in 2013. Here, PeeFence validated the functionality of the concept and the interest of the festival as future customers.

Cycle 2: Beta prototype

The goal for the following year was to improve the product design and produce 10 PeeFences to perform a real user test at Roskilde Festival. This led to new prototyping activities for five of the six the sub-functions. **(5)** Only the solution for providing a print on the PeeFence was directly transferred to the Beta prototypes. Regarding the **(6)** drain, **(7)** roll up, and **(8)** mounting, PeeFence switched to standard parts that could be used instead of their own 3D printed designs. In contrast to product cycle 1, PeeFence did not prototype multiple concepts in parallel, but simply tested potential solutions to their improvement areas until satisfied. **(9)** Finally, 12 beta PeeFences were produced and tested at Roskilde Festival 2014. This test confirmed that users were willing to use the product and that it successfully reduced the amount of urine and smell along the fences.

Cycle 3: PeeFence V1.0

At Roskilde Festival 2015, PeeFence was paid to deliver 190 urinals to the festival. The increase in number of produced products was the main driver for finding new solutions. PeeFence needed to consider production methods and scalability in their product design, which manifests on the ProtoMap. For the first time, PeeFence started

to prototype production methods. **(10)** To find a more scalable solution for the drain they tested whether they could produce their own funnel using thermoforming. **(11)** Despite promising tests using spray paint for the print, this solution proved not to be durable in harsh weather and they had to return to the sticker solution used in the Beta prototypes.

Cycles 4 and 5: PeeFence V1.1 and V1.2

The ProtoMap shows many similarities in the development of PeeFence V1.1 and V1.2. After V1.0, PeeFence were satisfied with their overall product design, but wished to optimize for faster production and ease of installation. Consequently, we observe a high number of iterations in product cycles 4 and 5, but only for a few of the sub-functions, e.g. **(12)**. For half the sub-functions, solutions are not prototyped or changed during these product cycles, e.g. **(13)**. **(14)** Product dimensions change so PeeFences fit standard pallets and **(15)** the tape that has been used to connect the funnel and hose is switched to a standard pipe connection. **(16)** Some of the changes within a sub-function automatically force design changes, and consequently prototyping, in other of the sub-functions to ensure that sub-solutions fit together when integrated.

Cycle 6: PeeFence V2.0

In 2017, two of the founders began to work fulltime and they secured external investment to the company. PeeFence began to grow their customer base and decided to change their business model from serviced rentals to direct sales, which led to a scale

up of production to 2500 V2.0 PeeFences. **(17)** This caused a reconsideration of the concept as a whole, which can be seen by the introduction of three new integrated concepts. Deciding to sell the product to customers, changed product requirements and caused an increase in prototyping activities. **(18)** We observe how new parallel concepts are prototyped in several of the sub-functions. **(19)** As the product would not be used by multiple different customers, the stickers were dropped in favor of printing graphical elements directly on the urinals. **(20)** Furthermore, the standard pipe connectors that were introduced in product cycle 5 were changed to an injection molded custom design. With V2.0 finished by the beginning of 2019, focus shifted to sales rather than further product improvements.

Quantifying Prototyping Strategies

In total, PeeFence produced 114 prototypes and made 60 explicit prototype tests. Table 2 breaks down the use of different prototyping strategies in each product cycle and the graphs in Figures 6-11 illustrate how the strategies changed over time. The graphs show that the prototyping strategies can change substantially between product generations. Rather than observing linear gradual changes in the strategies, they fluctuate across development cycles.

Figure 6 shows the prototype media used for each of the six product generations. In terms of media, physical prototypes were the most dominant in all product versions. While virtual prototypes were present across generations, sketches were only used formally in the very early product cycles. The number of produced

prototypes varies over the course of the product development process, with the highest number of prototypes produced in the first and last product cycles, which contain 25 and 27 prototypes respectively (excluding sketches). In contrast, only eight prototypes were produced in product cycle 4.

On Figure 7, we observe how functional tests constitute the core of prototype testing (7.3 tests in average), whereas only a few user tests (usually one) were conducted in each cycle. Thus, PeeFence's prototyping efforts have emphasized product functionality and optimization rather than the exploration of external feedback. As the scale of production increased in product cycle 3, testing of manufacturing processes also became a part of PeeFence's prototyping activities.

The use of integrated and isolated prototypes can be seen on Figure 8. PeeFence has employed a higher number of isolated prototypes than integrated prototypes, thus focusing their prototyping efforts on subsystems. Overall, 84% of prototypes were built to evaluate subsystems. Yet, in the later product cycles the number of integrated prototypes, where the whole product is prototyped together, start to increase. In the final product cycle, the percentage of integrated system prototypes is at its highest with 30%.

Figure 9 provides further detail on the use of isolated prototypes, as it shows the prototyping efforts that have been made for each individual function. It has been more challenging to find a satisfactory design for some functions than for others. The drain is the only function to be prototyped in all of the six product cycles, meaning that all six product generations have a different solution for the drain than the previous

generation. In contrast, the mounting of PeeFence onto fences has only been prototyped in three of the cycles. 28 prototypes were produced for the drain, while the assembly of funnel and trough required the smallest prototyping effort, needing only four prototypes until a satisfactory solution was found.

Figure 10 shows to what extent PeeFence has employed parallel or iterative prototyping strategies. More often, prototypes were used to iterate a concept than to test a parallel solution. In product cycle 2, the efforts are almost equal, with six parallel prototypes compared to eight iterations. In contrast, product cycle 5 produced only five parallel prototypes compared to 14 iterations. When 'Iterations per parallel concepts' increases, PeeFence has spent more time iterating concepts than they have exploring parallel solutions, as it is the case in product cycles 4 and 5.

On Figure 11, we see the different techniques that were used to fabricate the physical prototypes. Across six product cycles, PeeFence used nine manufacturing techniques to realize their prototypes. Each product generation was developed with the use of different techniques than the one before. For the Beta prototype, only two types of techniques were used, riveting and manual processes, while V2.0 combined six different techniques. The final product cycle is characterized by a reduction of manual processes and the introduction of more advanced techniques, such as injection molding.

Figure 11 shows that 3D printing was the dominant prototype manufacturing technique in the initial product cycle, and that it was reintroduced in the later cycles, but to a lesser degree. A closer look at this phenomenon can be seen in Figure 12, which contains sections of the ProtoMap where 3D printing was used with changing purposes

depending on the stage in the product development. First, it was employed in a diverging process to explore alternative designs, later to test a tool design for production, and finally, for the detailed engineering design of the injection molded pipe connections.

DISCUSSION

The following sections draw insights on the presented results to discuss prototyping in the context of the development process and address the research questions. The insights derived from our analysis provide a holistic overview of prototyping activities in a hardware startup, rather than specific stages of the development process.

How Prototyping Strategies Change from Early Phases to Later Phases of Development

Within the context of our case study, we observe that developing a new product or making radical changes to a design leads to a higher use of parallel and integrated prototypes, whereas optimizing a particular component causes an increase in iterations of sub-system prototypes. We also find that timing alone does not explain changes in the prototyping process, as it cannot account for the unpredictability of a startup's development journey.

Isolated Prototypes in Early Product Cycles and Integrated Prototypes in Late Cycles

PeeFence's prototyping strategy is characterized by a high use of isolated prototypes (Figure 8). Each product cycle follows a similar structure initiated by prototyping and testing of isolated concepts, followed by the combination of selected concepts into integrated prototypes. The first product cycle expands a 'morphological chart', that grows larger over each product cycle as new isolated concepts are explored [32]. Each new concept for a sub-function is a new sub-solution in the matrix, and it is synthesized with the other selected concepts at the end of each product cycle for the integrated prototypes.

Through the first product cycles, all functions are prototyped, while the later cycles focus on prototyping concepts for fewer functions. In 30% of the development cycles that take place at a sub-functional level, no new prototyping activities are initiated. As soon as a concept is proven and no new inputs are derived from prototype testing, that concept is no longer prototyped. For instance, the *roll up* function is not prototyped after cycle 3, after an optimal solution was reached. In this regard, our findings support the argument that isolated prototypes can help reduce time and cost by focusing the prototyping efforts on the most essential questions [12] and utilize individual strategies for each subsystem [16].

As isolated solutions are designed and tested, it remains unknown how they will affect each other when they are integrated [33]. Thus, the need for holistic prototypes and integrated tests increase with time. Towards product cycle 5 and 6, PeeFence starts to prototype integrated systems more frequently. Integrated tests are easier and quicker to make at late stages where the subsystems have been prototyped over several

iterations. Thus, PeeFence's prototyping strategies change from a high focus on isolated prototypes with few integration points, to a higher focus on integrated prototypes, where only selected subsystems are prototyped.

Parallel Prototypes for Early Identification, Iterations for Late Optimization

Figure 10 shows that the exploration of parallel concepts and iterations vary noticeably between the first and later product cycles. The initial product cycle shows a structured approach where several parallel concepts are iterated simultaneously until the end of the cycle, where the best concept is selected for each function. Needley et.al. consider this to be a good strategy as they observe that divergent prototyping improves the outcome of later iterations [34]. In the later phases, PeeFence usually iterates one concept at a time, until that concept is proven functional or not. At this time, they are not exploring various solutions, but reacting to specific design input. Therefore, they do not prototype alternative concepts, thus making their prototyping activities more effective.

However, we consider whether it also limits opportunities to innovate. The ProtoMap shows that the exploration of new alternatives on the integrated system level in cycle 6 triggers further prototyping of the mounting, material and print subsystems. Similarly, further exploration of alternatives on an isolated system levels may have triggered changes in the overall concept leading to further prototyping on an isolated system level.

Another interesting observation is related to the development of a high number of parallel concepts in the last development cycle. This increase in parallel prototypes can be attributed to the change of business model. PeeFence moves from a product/service offering to a sales-based offering that transfers the ownership of the products to the customers. Dow et al. describe how iterating one idea can cause fixation as no other concepts are considered [35]. Our case study supports this notion, as the increase in parallel prototyping is linked with the most radical product changes since the first product cycle.

We observe that parallel prototyping of integrated systems leads to more radical and innovative changes, while iterative prototyping of isolated systems leads to optimization of the product's functionality. PeeFence did not produce integrated prototypes in the first product cycle, before starting to prototype on an isolated level. Therefore, it remains unknown whether radical changes would have been made in earlier product cycles if parallel concepts on an integrated level had been explored earlier.

Changes in Prototyping Strategies Explained by Changes in Objectives, Scale of Production and Accumulated Knowledge

Considering the longitudinal development process of a product with multiple generations, one might expect to observe steady trends such as a constant decrease of parallel prototyping activities over time, as observed by [6]. As mentioned, Figures 6-11

show visible fluctuations in terms of the prototyping strategies used in our case study.

We argue that it is not effective to describe changes in prototyping strategies *only* in terms of the temporal aspects of the development process. Instead, we look at the reasons behind the change in strategies. We understand these reasons when we combine information from the PeeFence ProtoMap about what is prototyped at a given time with contextual information gathered through interviews. In PeeFence's case, we identify three main reasons that lead to change of prototyping strategies: (1) changing objectives based on previous prototype tests, (2) scaling production, and (3) increase or decrease in knowledge of solution space.

First, the choice of prototyping strategies depends on the specific objectives for a given product cycle. The objectives for product cycles 4 and 5 were to optimize for transportation and installation. Therefore, we find the highest number of iterations per parallel concepts in these cycles. Objectives were usually defined by findings from prototype tests rather than a project plan. Figure 7 shows that PeeFence has made several prototype tests in each product cycle, with a focus on testing functionality. Every integrated prototype test led to the acquisition of new knowledge that influenced the objectives and thus the prototyping strategies selected for the next product iteration.

Second, we identify that scaling the production across product generations is one of the main drivers for PeeFence's prototyping activities. We especially observe an increased number of prototypes in cycles 3 and 6; first from 12 to 190 and then from 300 to 2500 units. Each of these cycles correspond to changes in manufacturing

processes that result in changes in the design, which in turn leads to an increase in the number of prototypes.

Finally, we observe that the accumulated knowledge in the solution space affects the number of prototypes and the extent to which parallel concepts are explored (Figure 10). This is seen especially in product cycle 1, where PeeFence makes the first prototype with no previous knowledge and therefore make more prototypes than later cycles.

We believe that all three aspects; design objectives, production scale and knowledge of the solution space will evolve naturally over the development process. Objectives will change from proving initial concepts to detailing a design while production scale and knowledge of solution space will increase with time. Therefore, it can be valid to provide insights on the use of prototyping strategies in different phases, especially if a linear, well-defined product development process is followed. For instance, PeeFence's use of integrated tests increase with each iteration from product cycles 3-6, as it becomes easier and faster to make integrated tests over time.

Yet, unforeseen events may force designers to make radical design decisions and employ strategies from earlier development phases [1]. This is clearly seen in product cycle 6, where PeeFence changes their business model to fit demands from new customers. In this case, the product needs to adapt to a previously unexplored solution space that requires prototyping strategies that are suitable for new product development processes. Consequently, this change explains why product cycles 1 and 6 employ many similar strategies. Based on PeeFence's case, we conclude that guidance

on prototyping strategies can be tied to a specific time or product phase. However, when objectives, production scale, knowledge or other factors change and do not follow the expected process, the prototyping strategies must change as well [1].

How Prototyping Affects Product Realization

In this section, we observe how the choice of prototyping tools and medium can affect product realization both positively and negatively. Prototyping can be used strategically to find the right production methods, but the choice of manufacturing for early prototypes can also lead to a redesign of the product.

The Freedom of 3D Printing Can Lead to Altered Solution Designs When Scaling Up

In PeeFence's product development process, seven out of eight functions are fulfilled with a different concept than the one chosen in the first product cycle. Already from the Alpha to the Beta prototypes, three out of six solutions were changed. This was a surprise to the PeeFence founders who anticipated that only optimization of the final design would be needed after the Alpha prototype.

During product cycle 1, PeeFence focused only on proving their concept by making a functional prototype. As seen in Figure 11, PeeFence designed and 3D printed almost all components themselves, which allowed them to test several parallel concepts quickly. By not committing to a particular production method PeeFence had a larger freedom for experimentation in the early prototyping phase [16].

As the product evolved, the need for a more scalable solution became eminent as early as product cycle 2. However, only for one out of three sub-solutions, it was

possible to find standard parts similar to the 3D printed components that were prototyped earlier. Thus, the lack of consideration for production methods in the previous development cycle lead to the several redesigns. Design for manufacturing is considered to be one of the main challenges faced by hardware startups [36], and our analysis show that it was also the case for PeeFence, as they had to scale their production significantly in each cycle. Recent studies that investigate the negative consequences of additive manufacturing make similar conclusions [34, 35]. These show that designing for additive manufacturing leads to designs that are harder to manufacture using traditional processes, even when the designs are modified for conventional manufacturing. Nonetheless, using prototyping-focused technologies such as 3D printing can be considered as a reasonable tradeoff as it allowed PeeFence to test their ideas and gain feedback quickly.

Prototyping for Production

In the early phases of product development, designers simultaneously validate a product design and a production method, but later in the process, these have to be validated separately. Similarly, PeeFence does not only prototype to find the right product design, but also to find the right manufacturing or tool design. This means that there has been no “leaps of faith” in their process, as most product decisions are based on the outcome from prototype tests.

Figure 9 shows that manufacturing production tests are made first time in cycle 3. Increasing the number of produced products in this cycle introduced new requirements for the ease, duration and cost of production. Therefore, PeeFence did

not only test the feasibility of their design, but also their production methods. For instance, molds were 3D printed to validate the tool design for thermoforming before the final molds were milled in aluminum. This is a viable way to test a design or production method before investing in an expensive tool, similar to using 3D printed molds for injection molding [39].

The main limitation in prototyping for production is that even higher quality 3D printed parts do not have comparable characteristics to an injection-molded part. This makes it difficult to test the exact behavior of the performance critical parts, such as their self-designed pipefittings in V2.0. According to PeeFence, they were not able to test the solution to their satisfaction before ordering the rather costly production tools.

In summary, we observe that there is a significant shift in prototyping strategies across the multiple generations of the product. During the early product cycles, not being able to test a concept meant that they could not make it. In the later cycles, they were able to (and sometimes had to) produce their products through contract manufacturers, without being able to test them as prototypes. Thus, we find that the need for more advanced or conventional methods for larger scale manufacturing poses a challenge in terms of prototyping for production.

Evaluation & Perceived Value of the ProtoMap

From a research point of view, we believe that the ProtoMap provides a longitudinal perspective on hardware product development that is rather undocumented in the literature. However, we believe that this tool can also provide

valuable insights to practitioners. In this regard, we have conducted a semi-structured interview with the case company in order to evaluate their perceived value of the PeeFence ProtoMap.

Table 3 summarizes their evaluation, and it shows that PeeFence ‘agrees’ or ‘strongly agrees’ with four of the six statements. Specifically, they strongly agree that the ProtoMap accurately illustrates their development process (Q1) and agree that the documentation of prototypes can be valuable during a development process (Q6). However, documenting the prototypes themselves are not of highest importance to many hardware startups and PeeFence is no exception. What is often lost or forgotten is the knowledge that is inferred from the prototypes and the reasons why one concept was chosen over another. The ability to manage knowledge from prototypes in a visualization tool has a potential value for the practitioners and should be further explored.

PeeFence also ‘strongly agrees’ that the ProtoMap inspires them to make more deliberate strategic decisions in the future (Q4). This indicates that the ProtoMap not only documents a process, but also helps practitioners understand the importance of making deliberate prototyping strategies. We observe that the visualization triggers a reflection from PeeFence about their strategic decisions, facilitating a discussion of how they can gain a deeper understanding of the motivation and arguments behind different strategic decisions.

However, even though they are inspired to make more deliberate decisions in the future, PeeFence does not think that the ProtoMap in its current format can assist

them with this. To gain value from past insights, they need to be translated into actionable guidelines or checklists for future use. PeeFence sees a high potential for the ProtoMap to be the basis for such guidelines in the future.

Contribution and Future Work

This paper explores the value of visualizing the prototyping processes over an entire product development project. We consider three main contributions of this work as: (1) Validation and expansion of current visualization of prototyping processes through the ProtoMap, (2) new contextual insights on the use of prototyping strategies over a product development process, and (3) a beginning understanding for the support for practitioners.

The ProtoMap presents an expanded view of the theoretical model presented in Figure 1; but it is developed through an empirical study with an emphasis on the relationships between different prototyping activities. We suggest that the ProtoMapping approach is applied to more cases to validate and possibly expand it even further, until we achieve a general representation that can encompass the varying structures in different types of development projects.

In addition to representing the general nature of prototyping processes, ProtoMapping also presents a new way to generate knowledge about the use of prototyping strategies in the context of product development processes. The presented learnings from the case study could not have been gained only by interviewing the case company about their prototyping strategies or by analyzing each prototype in isolation. The learnings serve as examples of the value that can be generated from using such a

visualization to observe and analyze prototyping strategies in the product development process.

Through this case study, we gather knowledge on how and why the use of prototyping strategies change and the consequences that some strategic choices can have for the further process and product realization. While our findings cannot be generalized to other product development projects without further data collection, they allow us to concretize and contextualize our current understanding of the different prototyping strategies. Understanding the possible implications from different strategic decisions is valuable even though we may not know how often they occur.

The rich nature of the data captured in this case study further allowed us to identify other influencing contextual factors surrounding the prototyping activities. Naturally, this study alone does not present all the factors at play, but it provides first insights and proves the potential for future findings. Future studies should seek to increase the sample size, but also compare across different companies, design approaches and product domains.

It should be noted that we focus on a few strategic factors in this paper, but the model has the potential for visualizing several more, such as prototype fidelity or costs. Although, this case study sees PeeFence successfully bringing their product to market, it is unknown whether they could have done it faster or better if they had prototyped differently. Further expansion of the ProtoMapping technique to capture costs, fabrication time, or decisions made from prototyping can potentially allow us to assess the quality, efficiency and efficacy of the prototypes and prototyping activities.

This study also provides knowledge on how to utilize the generated knowledge for practitioners. The evaluation with the case company shows that there is a difference between using the ProtoMap for research and for product development in practice. The value for practitioners lies in the possibility to predict and improve future prototyping processes. This could be by answering practitioners' questions, such as "When do we start making integrated tests?" or by enabling them to better plan their future development projects. In that regard, it should also be explored whether design teams can use ProtoMaps 'in-situ' to map knowledge, navigate their own prototyping processes and determine a deliberate use of prototyping strategies during agile hardware development processes.

Limitations

The condensation and encoding of information that happens in a visualization process always compose a risk of producing an over-simplified or ambiguous illustration [41]. The need to maintain a readable visualization also puts a limit to the amount of data that can be included. The structure will enhance certain aspects of prototyping process and exclude others. Exploring digital and interactive versions of the ProtoMap could overcome the limitations of the current visualization.

During the early stages of development, we explored several alternative structures and selected the one that most accurately illustrated PeeFence's prototyping process. However, a different set of data or different research questions may have led to a different structure. It may be considered whether the ProtoMap is most suitable for projects where an evolutionary prototyping strategy similar to PeeFence's is employed.

However, as the identification of their prototyping strategies were an outcome of the visualization and not the starting point, we believe the ProtoMap to be applicable in many types of projects employing different prototyping strategies.

In the visualization process, a number of assumptions were made to be able to structure the data, such as our definition of a new prototype. For these assumptions, using other levels of abstractions will change the structure of ProtoMap and the consequent analysis. However, we assess that it will not change the provided insights and conclusions, which are also complemented by qualitative perspectives.

As discussed earlier, the inherent limitation of a single case study is its ability to provide generalized conclusions. The ProtoMapping technique presented in this paper allows us to characterize PeeFence's prototyping processes and infer insights, but we can only hypothesize about the transferability of our findings and conclusions to other cases. On the other hand, we believe that the longitudinality and the level of detail of the captured data makes this case study highly valuable, as it was possible to look deeper into the contextual effects of the investigated strategic factors.

CONCLUSION

This paper provides a case study of visualizing the prototyping activities in a hardware startup; from idea to production. An analysis of the developed ProtoMap provides a number of findings that leads to insights on the changes and effects of prototyping strategies in different parts of a product development process. We observe how the prototyping of parallel concepts, integrated systems, isolated systems and

iterations change over the course of the product development process. Further, we see how manufacturing methods in early stage prototypes can negatively affect product realization, but also how prototypes can be used strategically to prototype for production. Additionally, we find that timing is not enough to explain the change in strategies in a hardware startup.

While these insights are tightly coupled with the presented case study, they illustrate the value of visualizing a prototyping process through its prototypes. The analysis provides a ProtoMapping structure for the documentation of a prototyping process that can be applied to other cases. It allows for a retrospective identification and comparison of prototyping strategies in different phases of a product development process. Insights from a broader range of studies may allow us to formulate contextualized prototyping strategies and provide generalized guidance to practitioners to choose and employ prototyping strategies in different stages of product development.

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REFERENCES

- [1] Elverum, C. W., Welo, T., and Tronvoll, S., 2016, "Prototyping in New Product Development: Strategy Considerations," *Procedia CIRP*, pp. 117–122.
- [2] Elverum, C. W., and Welo, T., 2014, "The Role of Early Prototypes in Concept Development: Insights from the Automotive Industry," *Procedia CIRP*, pp. 491–496.
- [3] Camburn, B., 2015, "A Systematic Method for Design Prototyping," *Journal of Mechanical Design*, **137**(8), p. 081102.
- [4] Anastassova, M., Mégard, C., and Burkhardt, J.-M., 2007, "Prototype Evaluation and User-Needs Analysis in the Early Design of Emerging Technologies," *Human-Computer Interaction, Part I*, **4550**, pp. 383–392.
- [5] Camere, S., and Bordegoni, M., 2016, "A Lens on Future Products: An Expanded Notion of Prototyping Practice," *Proceedings of International Design Conference, DESIGN*, Dubrovnik, Croatia, pp. 155–164.
- [6] Böhmer, A. I., Hostettler, R., Richter, C., Lindemann, U., Conradt, J., and Knoll, A., 2017, "Towards Agile Product Development - The Role of Prototyping," *Proceedings of the International Conference on Engineering Design, ICED*, Vancouver, Canada, pp. 1–10.
- [7] Schuh, G., Dölle, C., and Schloesser, S., 2018, "Agile Prototyping for Technical Systems – Towards an Adaption of the Minimum Viable Product Principle," *Proceedings of NordDesign*, Linköping, Sweden.
- [8] Knapp, J., Zeratsky, J., and Kowitz, B., 2016, *Sprint: How to Solve Big Problems and Test New Ideas in Just Five Days*, Simon and Schuster.
- [9] Ries, E., 2011, *The Lean Startup*, Crown Publishing Group.
- [10] Menold, J., Jablokow, K., and Simpson, T., 2017, "Prototype for X (PFX): A Holistic Framework for Structuring Prototyping Methods to Support Engineering Design," *Design Studies*, **50**, pp. 70–112.
- [11] Tiong, E., Seow, O., Camburn, B., Teo, K., Silva, A., Wood, K. L., Jensen, D. D., and Yang, M. C., 2019, "The Economies and Dimensionality of Design Prototyping: Value, Time, Cost, and Fidelity," *J. Mech. Des.*, **141**(3), p. 031105.
- [12] Camburn, B. A., Jensen, D. D., Crawford, R. H., Otto, K. N., and Wood, K. L., 2015, "Evaluation of a Strategic Method to Improve Prototype Performance with Reduced Cost and Fabrication Time," *Proceedings of the International Conference on Engineering Design, DESIGN*, Milan, Italy, pp. 333–342.
- [13] Starkey, E. M., Menold, J., and Miller, S. R., 2019, "When Are Designers Willing to Take Risks? How Concept Creativity and Prototype Fidelity Influence Perceived Risk," *J. Mech. Des.*, **141**(3), p. 031104.
- [14] Jensen, L. S., 2018, "Design by Prototyping in Hardware Start-Ups," Ph.D. Thesis, Technical University of Denmark.
- [15] Lauff, C., Kotys-Schwartz, D., and Rentschler, M. E., 2017, "What Is a Prototype?: Emergent Roles of Prototypes from Empirical Work in Three Diverse Companies," *Volume 7: 29th International Conference on Design Theory and Methodology*, ASME, Cleveland, Ohio, USA, p. V007T06A033.

- [16] Christie, E. J., Jensen, D. D., Buckley, R. T., Menefee, D. A., Ziegler, K. K., Wood, K. L., and Crawford, R. H., 2012, "Prototyping Strategies: Literature Review and Identification of Critical Variables," *American Society for Engineering Education Conference*, San Antonio, TX, United States, p. 25.1091.
- [17] Lauff, C. A., Kotys-Schwartz, D., and Rentschler, M. E., 2018, "What Is a Prototype? What Are the Roles of Prototypes in Companies?," *J. Mech. Des.*, **140**(6), p. 061102.
- [18] Camburn, B. A., Dunlap, B. U., Kuhr, R., Viswanathan, V. K., Linsey, J. S., Jensen, D. D., Crawford, R. H., Otto, K., and Wood, K. L., 2013, "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment," *Proceedings of ASME IDETC/CIE 2013*, ASME, Portland, Oregon, USA, p. V005T06A033.
- [19] Thomke, S. H., 1998, "Managing Experimentation in the Design of New Products," *Management Science*, **44**(6), pp. 743–762.
- [20] Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., and Wood, K., 2017, "Design Prototyping Methods: State of the Art in Strategies, Techniques, and Guidelines," *Design Science*, **3**.
- [21] Yang, M. C., 2005, "A Study of Prototypes, Design Activity, and Design Outcome," *Design Studies*, **26**(6), pp. 649–669.
- [22] Ullman, D. G., 2010, *The Mechanical Design Process*, McGraw-Hill.
- [23] Ilg, J., Wuttke, C. C., and Siefert, A., 2018, "Systematic Prototyping of Product-Service Systems," *Procedia CIRP*, Elsevier B.V., Linköping, Sweden, pp. 50–55.
- [24] VDI Society for Product Development, Design and Marketing, 1987, *Systematic Approach to the Design of Technical Systems and Products*, Verein Deutscher Ingenieure.
- [25] Seow, O., Tiong, E., Teo, K., Silva, A., Wood, K. L., Jensen, D. D., and Yang, M. C., 2018, "Design Signatures: Mapping Design Innovation Processes," *Proceedings of ASME IDETC/CIE 2018*, ASME, Quebec City, Canada, p. V007T06A046.
- [26] Camburn, B. A., Arlitt, R., Perez, K. B., Anderson, D., Choo, P. K., Lim, T., Gilmour, A., and Wood, K., 2017, "Design Prototyping of Systems," *Proceedings of the 21st International Conference on Engineering Design, ICED*, Vancouver, Canada.
- [27] Tjalve, E., 2003, *Systematic Design of Industrial Products*, Institute for Product Development, Technical University of Denmark.
- [28] Otto, K. N., and Wood, K. L., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall.
- [29] Likert, R., 1932, "A Technique for the Measurement of Attitudes," *Archives of Psychology*, **22**, pp. 5–55.
- [30] Takeuchi, H., and Nonaka, I., 1986, "The New New Product Development Game," *Harvard Business Review*, **64**(1), pp. 137–146.
- [31] Connell, J. L., and Shafer, L., 1989, *Structured Rapid Prototyping: An Evolutionary Approach to Software Development*, Yourdon Press.
- [32] Zwicky, F., 1948, *The Morphological Method of Analysis and Construction*, California inst. of technol.

- [33] Bracken, J., Brennan, S., Lissenden, C., Simpson, T. W., Van Sant, I., Reichard, K., and Ng, M., 2018, "Change Propagation During Prototyping: A Case Study of a Robotic Inspection System for Dry Nuclear Waste Storage Casks," *Proceedings of the ASME IDETC/CIE 2018*, Quebec City, Canada, p. V007T06A041.
- [34] Neeley, W. L., Lim, K., Zhu, A., and Yang, M. C., 2013, "Building Fast to Think Faster: Exploiting Rapid Prototyping to Accelerate Ideation During Early Stage Design," *Proceedings of ASME IDETC/CIE 2013*, Portland, Oregon, USA, p. V005T06A022.
- [35] Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., and Klemmer, S. R., 2010, "Parallel Prototyping Leads to Better Design Results, More Divergence, and Increased Self-Efficacy," *ACM Transactions on Computer-Human Interaction*, **17**(4), pp. 1–24.
- [36] Jensen, L. S., and Özkil, A. G., 2018, "Identifying Challenges in Crowdfunded Product Development: A Review of Kickstarter Projects," *Design Science*, **4**.
- [37] Abdelall, E. S., Frank, M. C., and Stone, R. T., 2018, "Design for Manufacturability-Based Feedback to Mitigate Design Fixation," *J. Mech. Des.*, **140**(9).
- [38] Abdelall, E. S., Frank, M. C., and Stone, R. T., 2018, "A Study of Design Fixation Related to Additive Manufacturing," *J. Mech. Des.*, **140**(4).
- [39] Zhang, Y., Pedersen, D. B., Mischkot, M., Calaon, M., Baruffi, F., and Tosello, G., 2018, "A Soft Tooling Process Chain for Injection Molding of a 3D Component with Micro Pillars," *J. Vis. Exp.*, (138).
- [40] Flyvbjerg, B., 2006, "Five Misunderstandings about Case-Study Research," *Qualitative Inquiry*, **12**(2), pp. 219–245.
- [41] Bresciani, S., and Eppler, M. J., 2008, *The Risks of Visualization: A Classification of Disadvantages Associated with Graphic Representations of Information*, ICA Working Paper 1/2008, Institute for Corporate Communication, Università della Svizzera italiana.

Table Caption List

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Table 1 Strategic factors included in this research

Factors	Characteristics	Visualized by
Prototype media	Hand sketch, virtual model, physical model	Single prototype attribute
Manufacturing technique	[type of manufacturing technique for physical prototypes]	Single prototype attribute
Prototype test	Functionality testing, user testing, process testing for manufacturing	Single prototype attribute
System level	Integrated, isolated	Visualization structure
Parallel prototyping	[number of parallel concepts]	Visualization structure
Iterations	[number of iterations]	Visualization structure

Table 2 Overview of strategic decisions in each of the six product cycles

	Alpha	Beta	V1.0	V1.1	V1.2	V2.0	Total
Prototyping media (Fig. 6)	40	9	16	8	14	27	114
Virtual	11	1	4	2	4	10	32
Physical	14	7	12	6	10	17	66
Sketch	15	1	0	0	0	0	16
Prototype test (Fig. 7)	11	6	14	5	10	14	60
Functional test	10	5	7	4	7	11	44
User test	1	1	1	1	1	1	6
Manufacturing process test	0	0	6	0	2	2	10
System level (Fig. 8 and 9)	40	9	16	8	14	27	114
Integrated	3	1	1	2	3	8	18
Isolated	37	8	15	6	11	19	96
Parallel prototyping (Fig. 10)	19	6	10	3	5	14	57
Iterative prototyping (Fig. 10)	28	8	16	8	14	23	97
Manufacturing technique (Fig. 11)	13	6	11	5	8	13	56
3D printing	8	0	0	1	1	1	11
Manual	4	5	6	1	4	1	21
Print	1	0	0	0	0	3	4
Riveting	0	1	0	0	0	0	1
Thermoforming	0	0	1	2	2	3	8
Water cutting	0	0	2	0	0	0	2
Milling, welding, turning	0	0	2	1	1	0	4
Injection moulding	0	0	0	0	0	1	1
Stamping	0	0	0	0	0	4	4

Table 3 Evaluation from case company. Responses are given on a five point Likert scale

Question		Response
Q1	The visualization accurately illustrates our development process	5
Q2	The visualization provides us with new insights about our prototyping activities, we didn't know before	4
Q3	Insights from the visualization can teach use how to improve our prototyping activities in the future	3
Q4	The visualization inspires us to make more deliberate prototyping strategies in the future	5
Q5	The documentation of our past prototypes is valuable to us in our future work	3
Q6	The documentation of prototypes could have been valuable to our team during our development process	4

Fig. 1 Camburn et al.'s prototyping strategy space expanded from iterations and prototyping of parallel concepts [20]

Fig. 2 The research methodology consists of four phases: Data collection, data visualization, data analysis and final evaluation

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Fig. 5 ProtoMap visualizing PeeFence’s prototyping processes. Five integrated concepts have been prototypes, while eight sub-functions have been explored through prototyping of 34 isolated concepts. Areas of interest have been numbered on the figure and are referred in the text. A detailed version of the ProtoMap is available at www.prototypingplanner.com. Further explanation of the elements in the ProtoMap can be found here for those interested in ProtoMapping themselves

Fig. 6 The prototype media used for each of the six product generations

Fig. 7 The types of prototype tests performed in each product cycle

Fig. 8 The use of integrated and isolated prototypes in each product cycle

Fig. 9 Number of prototypes produced for each function in each product cycle

Fig. 10 The use of parallel concepts and iterations in each product cycle

Fig. 11 The different manufacturing processes used to fabricate the physical prototypes in each product cycle. The technique indicated as ‘manual’ include the use of various hand tools

Fig. 12 3D printing has been used with different purposes in different product cycles