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ORIGINAL ARTICLE

Prototyping in practice – Paths and partners for testing novel industrial product and service ideas

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ABSTRACT

Prototyping is a core activity when developing new products, processes, and organisations alike. This paper describes the prototyping activities of 31 engineering design professionals in a high-technology industrial company. Findings examine the distribution of different types of activities across different phases of development based on thematic interviews. Examining 62 prototyping and testing pathways, we found that most prototyping paths started with the practitioners' own activities. These pathways were more likely to lead to prototyping paths with increased prototyping steps, than if the first prototyping activity took place in collaboration with a stakeholder. Overall, the pathways were short, which may indicate a lack of iteration. Both internal and external stakeholders were involved in collaborative prototyping, which was enabled by personal and unit level relationships. It was noted that different stakeholders were involved in different phases of development. Taken together, our results suggest that practitioner attention in prototyping may focus on latter development phases and demonstrate less iteration than what literature might suggest. In addition, findings highlight that opportunities for prototyping often depend on personal networks in the high-technology context if flexible prototyping budgets are not possible. We suggest organizations pay attention to supporting collaboration and prototyping throughout development processes.

Keywords: Prototyping; Collaboration; Idea advancement.

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INTRODUCTION AND THEORETICAL BACKGROUND

All product developers, designers, and professionals with a focus on development face multiple occasions where they must test their ideas and assumptions to be able to make informed decisions regarding the development object, context, or direction. Extant research has identified a wide array of prototyping tools, methods, and purposes. For example, workflow simulations, storyboards, mock-ups, scaled prototypes, virtual models, AR, and full-scale models (Camburn et al., 2017) are amongst the vast array of techniques for prototyping. In many companies, the COVID-19 pandemic further supported the inclusion of digital prototyping practices (Hölttä-Otto et al. 2023). The rise of design thinking and service design has further broadened the types of actors and contexts leveraging prototyping practices, as prototyping is a central practice in both (Fayard, Stigliani & Bechky 2017; Micheli et al. 2019).

Research has documented a range of benefits to prototyping, including evaluation of ideas, concept testing, gaining a deeper understanding of the context, creating new ideas, communicating with both the internal team and external stakeholders (Lim et al., 2008), promoting active learning (Camburn et al., 2017), and providing support for iteration by encouraging learning through failure in the early phases of development (Micheli et al., 2019). Prototyping in an iterative manner correlates with being able to better meet complex design requirements, as well as generating new ideas (Camburn et al., 2017). Different levels of prototypes at different stages of a development process can have an important role in knowledge transfer between different stakeholders (Simeone et al., 2017). Prototypes also help answer questions that arise during a design process (Houde and Hill, 1997). Prototyping in collaboration with others has also many benefits, from the very start of a project until the final design is ready. It is an effective activity for sharing knowledge with various stakeholders (Bogers & Horst, 2014), testing hypotheses and potential different frames (Paton & Dorst, 2011) to the problem at hand, and it allows trying out something that does not yet exist (e.g., Sanders, 2010). However, sometimes it can be tricky to understand what to prototype, with whom, with which techniques, and to set the objective of prototyping (Camburn et al., 2017).

Furthermore, while building mock-ups, creating simulations, creating scale models, and other types of prototypes is a good way to test ideas quickly, evaluation needs to be meaningful and in line with the goals of prototyping in the first place (Camburn et al., 2017). Thus,

it is essential to plan the prototyping and testing activities and think about how they support the development process (Lim et al., 2008). Depending on the objective of prototyping activities, there are typically three aspects that are prototyped; implementation, look and feel, and role (Houde & Hill, 2017). These prototypes can be of varying fidelity, ranging from low-fidelity card-board models to high-fidelity functional and polished prototypes.

Yet despite the documented benefits, it is unclear to what degree and with whom prototyping is practised in different contexts. For example, those new to design approaches may find it hard to iterate ideas (Rekonen & Hassi 2018), and even experienced professionals may not make use of the array of methods available. Laakso and Liikkanen (2012) noted that structured methods for e.g., idea generation and rapid prototyping were used only scarcely amongst the studied creative professionals. While prototypes in companies have various roles and there are differences in how prototyping is carried out in practice, it is an underexplored part of design practice (Lauff et al., 2018). This study investigates prototyping in practice to foster a better understanding of the status quo and understand the methods, with whom, and to what extent prototyping takes place in industry. This understanding is needed in order to create practices supporting prototyping ideas.

METHODOLOGY AND ANALYSIS

The case and data collection

The data was collected as a part of a larger research project, where the authors were responsible for planning the data collection and two of the authors conducted the interviews. Thirty-one semi-structured thematic interviews (Qu & Dumay, 2011; Braun & Clarke, 2006), focusing on critical incidents, were conducted with engineering design professionals working in product development of physical business-to-business products and services within a single industrial technology company. The case organization was a multinational organization with several different business lines and units, operating in a traditional, technology heavy industry requiring primarily development cycles measured in years and a high degree of customization for industrial clients. The studied organization had a strong focus on development and technology leadership, with a large expert workforce, yet was also aiming to improve their innovation practices. As such, the case was chosen to offer a balance between a shared organizational and industrial context across the interviewees, yet variance in terms of different product and business lines and local resources and networks available to different engineering design professionals in the organization. The average tenure of the interviewees in the organization averaged at ten years, ranging from two to 30 years. Focusing on critical incidents allows the interviewees to tap into their memories of meaningful experiences and can limit recall bias (Chell, 1998; Flanagan,1954).

Data Analysis

The interviews focused on advancing ideas, and to collect descriptions of varying incidents, the interviewees were asked to describe both well received and rejected ideas, as well as instances where they collaborated or where their ideas resulted in filing invention disclosures. The projects these ideas were linked to were not tracker as a part of this study. As follow up questions, the interviewees were asked if the ideas were prototyped or tested. The interviewees were not provided with a definition of an idea or of a prototype by the researchers. The interviews lasted an average of 52 minutes, and were audio recorded and transcribed verbatim.

The interviews were thematically coded to identify recurring patterns in the prototyping activities described across the data. First, all instances where the interviewees talked about testing, trying something out, or prototyping were tagged in the interview transcripts. Second, these segments were further categorised according to the type of stakeholders involved in the activity, the number of prototyping iterations or steps described, the type of prototype or testing taking place, and the phase of the development process where the instance took place. The analysis resulted in 62 individual prototyping *paths*. For example, the following quote was found to illustrate testing the prototype with a customer in the latter stages of a product development process:

> "Then we will move on to a plant facility where we have a lot of business otherwise as well. We have these partnering plants where we do a lot of product development in collaboration with them."

RESULTS

The resulting 62 prototyping paths show that in addition to prototyping by themselves, product development professionals included a range of stakeholders in their prototyping and testing activities in varying stages of the development process. The main stakeholder groups found in the analysis were other internal units or laboratories in the company and external stakeholder groups including customers, subcontractors, manufacturing suppliers, universities, and consulting companies. There were also other individual mentions, such as having a helping hand at the laboratory facilities, that did not fall under any of these categories.

The interviews demonstrated that prototyping was dependent on how familiar the interviewees were with prototyping activities overall, what kind of knowledge they had of prototyping possibilities, and what their connections or network enabled them to pursue. The interviewees described having found their own ways and processes for prototyping and testing out their ideas

instead of having a company or unit wide shared process. For example, one interviewee had started testing at home:

> "The first things that I made - at home - were built out of legos. Like a first prototype and using it under the kitchen faucet to see how the water runs in the structure. So small toys can well be used to explore these concepts. [...]Then showing the rest of the team a video on my phone, that I tested this kind of thing, and it works well."

The type of prototyping they engaged in varied - some interviewees described mostly prototyping through 3D-modeling or simulations, for example noting that physical prototyping of ideas was not possible due to the size of their products. Others described a fair amount of physical prototyping with hand tools and other small manufacturing machines in the company facilities. The interviewees' descriptions of prototyping possibilities revealed that even inside the same organization some teams had better opportunities for physical prototyping than others. Most prototyping activities were described as starting with one's own individual effort, usually as a drawing or using 3D-modelling. Simulations were often mentioned, as the next step after modelling and drawing to make sense of the idea. Low-fidelity physical prototypes in the early phases of ideation and development were mentioned by only a few interviewees. Instead, physical prototypes were usually made when the product specifications were already quite clear.

Prototyping facilities or laboratories at the company were utilised when interviewees had access to them. Lack of access to internal prototyping facilities often led to prototypes being manufactured and tested by other units, the company's test laboratories usually located in other geographic locations, or with the help of subcontractors. Here the interviewees' connections, knowledge of external opportunities, and networks they had access to played an important enabling role. Those that had close connections with subcontractors worked with them to manufacture and test prototypes, while those that were closer to the customers more often took the prototyping activities more often to the customers' environment.

Prototyping paths and different stakeholders

Most of the described prototyping instances were paths of either only one step (n=23, 37%) or two steps (n=19, 31%). Longer iterative prototyping paths were in the minority, with 15 (24%) three-step paths described and only five (8%) paths with four or more steps (see examples of two different paths in Figure 1).

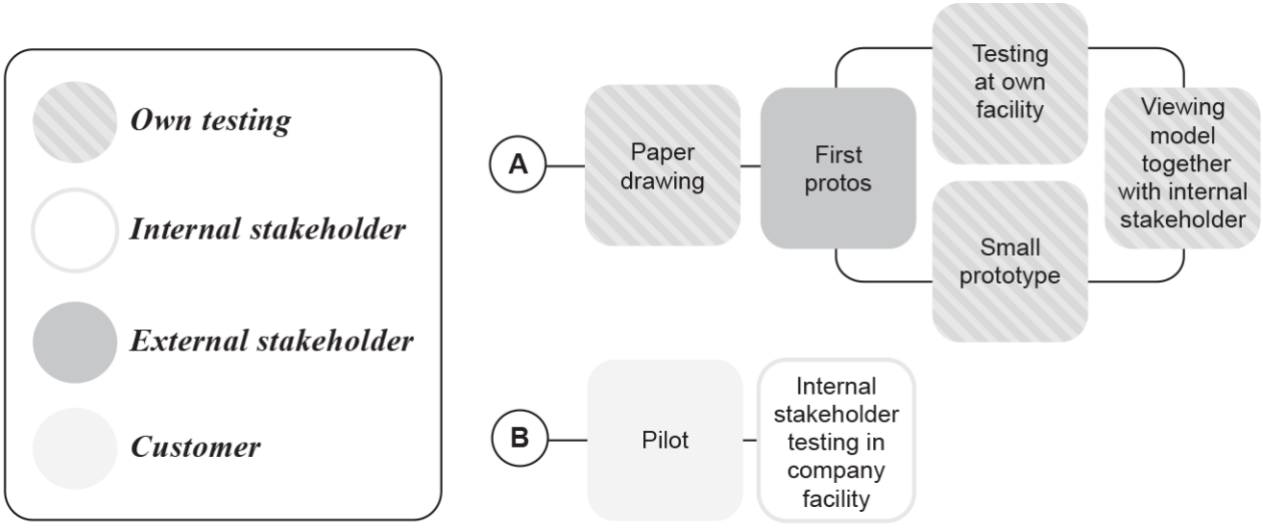

Fig. 1. Two prototyping paths (labelled A and B) showing different stakeholders and number of steps.

In most paths (n=33, 53%), the first prototyping activity took place in the unit where the idea was conceived, typically by the interviewees themselves. These prototypes included drawings, 3d-models, testing in a laboratory, 3D-prints, and other types of small-scale testing. When prototyping had started as individual work, it most often continued to a second round of individual prototyping before collaborative prototyping and testing with other units, subcontractors, or customers. Especially real scale, physical, material or manufacturing prototypes were often described to be only possible with subcontractors and customers. In these cases, the third round most often took place already with customers. Almost all paths with three or more steps started with prototyping by the interviewees. Piloting a proof of a concept with an internal stakeholder before the technology could be sold to an interested customer was described by one interviewee as follows:

> "The pilot equipment has been going through test runs in [the facility], and now the second pilot generation is about to be ready. If we can now use that to prove the functioning, then we can expand this equipment into a commercial scale. We have planned, and a lot has been already invested in the development of the commercial scale equipment, too."

In other instances, prototyping was immediately started in collaboration with another stakeholder (n=29 paths). In 13 instances (21%) this was an internal stakeholder, while the customer was involved in the beginning in nine instances (15) and other identified stakeholder groups only in seven instances (11%). When paths started in collaboration, they were very rarely described to have more than two steps - with only two such paths described, both having started with internal stakeholders.

The way these descriptions of prototyping instances were positioned relative to different development phases (see Figure 2) clearly indicates that prototyping with the customer usually happened closer to the release of the product. Customer involvement in prototyping was often described, for example, in cases where the first sold deal was the pilot testing of a product under development. Pilot testing was also described to be done in a lab or with subcontractors, illustrating the many meanings "piloting" had to the interviewees.

In the early phases of development, the interviewees tested their ideas with the methods easily available to them. The early phases often also included prototyping and testing mechanical designs with subcontractors and manufacturing suppliers. These collaborators were described to be experts in specific areas; thus, their help was described as important. The company had formed long and strong relationships with many different partners. Subcontractors were often used for manufacturing prototypes, as the company's own opportunities for prototype manufacturing were quite limited. The situation was described by two interviewees:

> "At least I would like it if we would have an easy access test laboratory, where one could make some crazy inventions quickly. Of course, it would be preferable, that there would be a 3D-printer that could be used or some tools that could be used to make initial models, like quick and dirty testing, that kind of opportunities would make innovating easier for sure. "

> "In practice if we want to do physical testing, then the case is that we are testing and making protos with some subcontractor."

Testing was also often moved to a customer's environment, where prototyping was described to consist of piloting, gathering data or testing in a real use environment. Some customers were described to have long traditions of being test and development partners, often as the first buyers for novel products. There were even mentions of further developing the product with the same customers after the product was already launched for sale. Some interviewees mentioned the first testing taking place with an already paying customer and described this as a risky process, when there was no certainty of the product being a success.

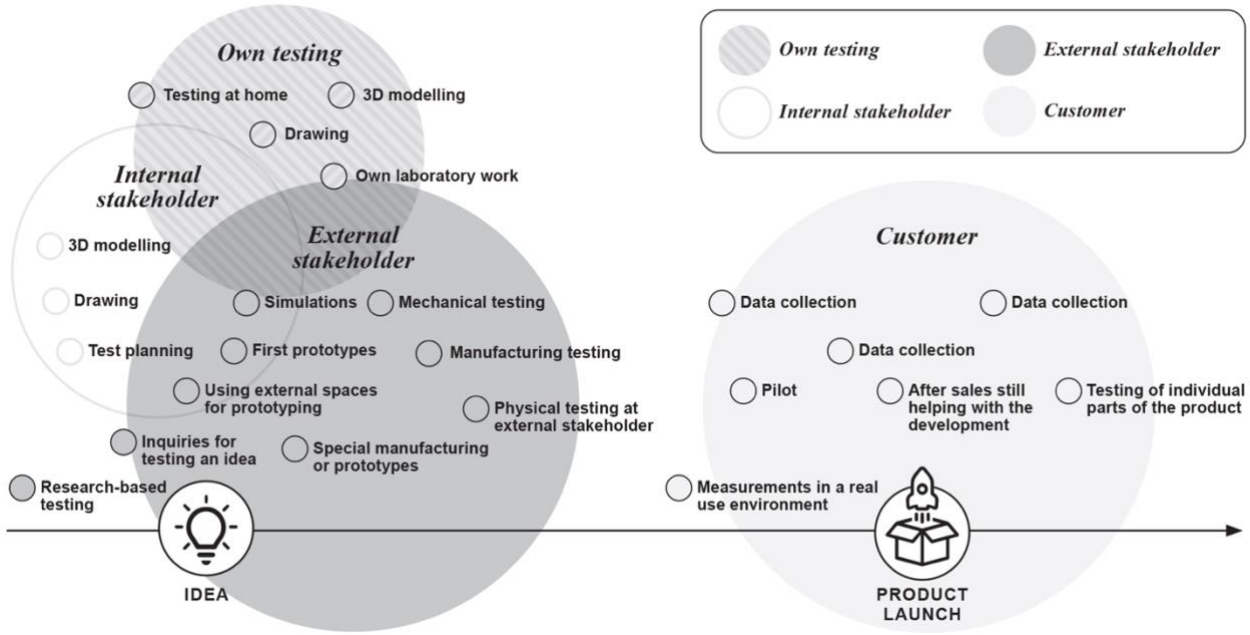

Fig. 2. The identified prototyping partner stakeholder groups and types of prototypes mapped to a timeline.

DISCUSSION AND CONCLUSIONS

How the practitioners perceived and discussed prototyping differed from how the literature typically represents prototyping (e.g., Camburn et al., 2017; Lim et al., 2008). Despite traditional product development process descriptions emphasizing the need for prototyping varying aspects, a stage-gate (Cooper, 1990) type of process does not always support iterative prototyping in the early phases of development. There was a lot of variances in what the interviewees meant by testing and prototyping. This illustrates the complex nature of the practice of prototyping, and varying expectations that different people may have of what a prototype is (Houde & Hill, 1997). The interviewees discussed mostly testing final prototypes or piloting, rarely mentioning low-fidelity prototyping. This suggests that often early steps in idea development, that are regarded as prototyping activities in literature, are either not considered prototyping in the practitioners' minds or then are easily skipped when moving to designing for production for example. Under-prototyping, in turn, can lead to lost opportunities for idea generation and knowledge sharing. Generating ideas in a visual modality, for example through prototyping, is one mechanism that can promote coming up with new ideas (Kirjavainen & Hölttä-Otto, 2021) and prototypes working as stimulators can help developers move beyond already existing ideas (BenMahmoud-Jouini & Midler, 2020). Yet most of the described prototyping paths had only one or two steps, indicating a lack of iterating in practice. Given research demonstrating iterative prototyping correlating with better chances of having new ideas and meeting the design requirements (Camburn et al., 2017), our findings point to possible missed opportunities in the field. Although the current study was based on retrospective data from a single organization and, as such, cannot be generalised to represent product developers in general, the results suggest that organizational support and creating a low threshold for prototyping, factors potentially leading to more iterations, may be a meaningful aspect to consider in all product development organizations. Further research could examine the skills that are needed to increase iterative prototyping or the potential return on investment (ROI) of prototyping in product development organizations, which might help in securing the needed resources for early development. The value of prototyping has been studied e.g., amongst student teams (Nelson & Menold, 2020), but the knowledge often needed for justifying prototyping resources to management remains scarce.

Second, the results highlight the significance of the personal networks of innovators. It is known that people who are central in networks have more power in taking ideas forward and are more likely individually involved in innovation (Ibarra, 1993). Those that had connections to external stakeholders and had collaborated with them in prototyping before turned often to their existing connections. Similarly, interviewees who had experience in inhouse prototyping, using the company's laboratory units, or that had strong connections with customers reported turning to them for help. Collaborative prototyping like this supports cross-organizational knowledge sharing and designing on the go (Bogers & Horst, 2013). These paths were described as easy and commonly used. Conversely, interviewees lacking pre-existing connections described prototyping and testing to be hard or in some cases even impossible. The importance of networks was further emphasised by an experienced lack of funding in R&D for prototyping and testing, particularly at scale in the expensive industrial technology context. This often led developers to defer fully testing new ideas only at a paying customers' facility, a potentially risky move. Prototyping in collaboration can also lead to improved prototyping, or at least bring in more diversity to the process, as professionals from different fields tend to have differing prototyping practices. For example, designers and engineers tend to prototype different aspects in different phases of a product development process with engineers putting emphasis on prototyping in proof of concept, and prototyping for manufacturing phases (Yu et al., 2018). As such, examining the interconnections in networks, prototyping practices and risk offers a promising research avenue for further understanding the dynamics of how ideas are advanced in organisations. While the current study was limited to self-reported data from a single source, further studies could explore how different stakeholders perceive and value instances of collaborative prototyping, extending our understanding of collaborative dynamics and offering data triangulation opportunities.

Taken together, to take full advantage of prototyping in different phases of a product development process, for example in generating new ideas, creating understanding, and advancing ideas (Lim et al., 2008; Camburn et al., 2017) organizations should support collaboration, and purposeful prototyping from the very start of a development process. A good idea is only a starting point for innovation and the true work lies in the successful implementation of creative ideas through development (Amabile, 1988), such as testing, prototyping, and learning.

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