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A study of the similarities and differences between engineers and designers
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Prototyping in theory and in practice: a study on the similarities and differences between engineers and designers

Abstract

Prototyping can be seen as the heart of the innovation process. Typically, engineers and designers both work on prototyping activities, but their diverse backgrounds make for different perspectives on prototyping. Based on earlier literature, this study investigates commonalities and differences in the prototyping behaviour of engineers and designers. For this study, semi-structured interviews and workshops with different experiments were conducted. Using low fidelity prototypes, our results indicated that there are differences in the early phase of prototyping. Engineers focused on the features and functions of a prototype and needed to meet specific goals in order to push the process forward. Designers, on the other hand, used prototypes to investigate the design space for new possibilities, and were more open to a variety of prototyping materials and tools, especially for low fidelity prototypes. In the later prototyping phases, the prototyping behaviours of engineers and designers became similar. Our study contributes to the understanding of prototyping purposes, activities, and processes across disciplines, and supports the management of prototyping in new product development processes.

Keywords: Prototyping theory and practice, engineers and designers, cross disciplinary, new product development

Introduction

As indicated in the “coupling” model of innovation (Rothwell, 1994), prototype development is one of the most essential parts of the innovation process, linking the early phase of ideation to manufacturing. The term prototype has been widely used in different disciplines, but its definition is not consistent. For example, Naumann and Jenkins (1982) stated that a prototype system “captures the essential features of a later system” (p. 30), while Beaudouin-Lafon and Mackay (2003) described a prototype as “a concrete representation of part or all of an interactive system” (p. 1007). The first definition focuses on the features of the object. This is a more typical engineering perspective, where the engineers hope to realize, test, and rework the features of a prototype for a later system. The second definition is more from the design perspective, which stresses interaction with different stakeholders through use of a prototype, a tangible artefact, allowing clients to envision and reflect on the final system (Beaudouin-Lafon and Mackay, 2003). These definitions underscore the different prototyping purposes from the two different disciplines. With new societal challenges and the development of complex systems, interdisciplinary collaborations are becoming more and more important, especially from designers and engineers, who are both actively involved in product development. The major motivation of this study is to have a clear understanding of prototyping behaviours from both an engineering perspective and a design perspective. Considering prototyping is part of the new product development (NPD) process, which is defined as “the transformation of a market opportunity into a product available for sale” (Krishnan and Ulrich, 2001, p. 1), we expect that the findings of this study will improve the prototyping procedure in the NPD process, as well as support and enhance teamwork in an interdisciplinary setup.
Because design is a generic term, which can be further classified as architectural design, industrial design, interaction design, etc., we wish to clarify that in this paper, design refers to industrial and interaction design with a focus on the form of the product, user experience, and behavior (Kirkham, 1999; Cooper et al., 2007). Moreover, in these design fields the products' technology is linked to mechatronics engineering research.

The structure of this paper is as follows. First of all, a brief overview of the prototyping purposes and processes with a focus on both engineering and design perspectives is provided. Next, we describe our study design, which was based on the literature and includes both semi-structured interviews and experiments. The methods and results are described in the following section. Finally, we compare our findings to previous studies in the discussion. The limitations of this study and our future work are presented at the end of this paper.

**Brief overview of prototyping in literature**
The term prototyping is very often seen in engineering, design, and other disciplines, but there is no agreement on a common definition. There is not a clear distinction between views of prototyping as a concept, an approach, a method, or a technology (Exner et al. 2015). A number of studies have attempted to analyze prototypes from different perspectives. For example, Houde and Hill (1997) presented the idea that the goal of prototyping could be providing a new functionality, presenting a known functionality in a new way, or using a new technique. Beaudouin-Lafon and Mackay (2003) categorized prototypes using four different characteristics: representation, precision, interactivity, and evolution. These efforts provide a good understanding of prototyping purposes and stages, but human involvement, especially from different disciplines, was not as highly considered. Warfel (2009) described that a prototype, in traditional engineering fields, represents a preliminary version of a product or product component. It provides information on the performance and quality of the product, as well as the life cycle and manufacturability. In the discipline of design, prototyping efforts are focused on manifesting and exploring designers' ideas, in an effort to gain knowledge and envision the final solution (Lim et al. 2008), to identify unknown issues and new opportunities (Dow and Klemmer 2011), to get the tangible feeling of the idea and discuss concepts with the users (Houde and Hill, 1997), and to involve users in the development process (Hillgren et al., 2011).

The prototyping processes mentioned in many engineering articles are usually in a specific domain, e.g. a specific solution for a certain problem. Only a few studies describe the general prototyping process in engineering as a kind of technology of its own. One notable example of such a generic prototyping process has been presented by Warfel (2009). As shown in figure 1, it identifies the basic procedures of a prototyping process: sketch, present, critique, prototype, and test, with the consideration of iterative and evolutionary processes. In the design literature, design process, instead of prototyping process, is more commonly used. In this context, Löfqvist (2010) introduced a modified generic design process model based on Cross's (2008) Four-Stage Model. This model includes exploring the problem, generating and evaluating the solutions, and communicating and incorporating changes into the next process (see figure 2). Although this design process model is not directly developed for the prototyping process, we can use it to reflect the prototyping process from a designer's perspective. In comparing the two models, we see that they have similarities in solution generation and evaluation with the consideration of iterative loops, but the design process model
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includes exploration of the problem at the beginning and communication afterwards, which are not considered in the engineering prototyping process model. Prototype building is also a key step of the generic design thinking process (Geissdoerfer et al. 2016, see figure 3). The design thinking method is a human-centred approach that focuses on incorporating people’s concerns, interests, and values into the design process, and employs rapid prototypes to find out feasible solutions for complex problems (Brown 2008, Meinel and Leifer, 2011, Geissdoerfer et al. 2016). As shown in figure 3, it follows two divergent-convergent phases, namely to understand, observe, and define the problem, then ideate, prototype, and test the solutions. It requires interdisciplinary collaboration.

Hatchuel et al. (2005) presented a design-space-value-management (DS-VM) model to analyse the design process, in which design space was defined as “a collective working place where designers can act to learn about what they want to learn for their overall design process” (p. 345). Based on this, the model could represent the development process as a sequence of design spaces, moving through functional space, phenomenological space, and device space, which are derived from and return to the value management level, as depicted in figure 4. It implies that designers place consideration on the surroundings in addition to the focus on a device or a prototype. In addition, this model has also been applied in a context where designers and engineers collaborated together. Arrighi et al. (2015b) relied on this framework to address generative constraints and cumulative sets of rules in managing radical innovation, a situation in which both engineers and designers were involved. In addition, there are also other design theories and design methods support prototyping activities. For example, the concept-knowledge design theory has been used to clarify the conditions when designing a new prototype (Hatchuel and Weil, 2009). Moreover, infuse design theory increases designers’ capacity and supports effective cross disciplinary collaboration (Shai and Reich, 2006). In order to enhance the understanding of prototyping process, Exner et al. (2015) generated another prototyping process model as depicted in figure 5. This three-phase prototyping process model was created based on a two-day workshop with prototyping experts from different disciplines. The model is still a generic model but has a higher level of detail. We referenced this model in our study for several reasons. First of all, the model was built from an interdisciplinary collaboration including engineers and designers, which meets the objectives of our study. Moreover, the model describes the different phases of prototyping and considers the distinct purposes as well as the iterations in each phase. Finally, it describes the common procedures for interdisciplinary development tasks that can be applied to most disciplines.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Moreover, several studies have addressed different behaviours regarding creativity and ideation between industrial designers and engineers. When they were asked to perform creative tasks, industrial designers focused on visual attributes, whereas engineers concentrated on performance (Wallace and Jakiela, 1993). Regarding their knowledge structures, Le Masson et al. (2016) indicated
that industrial designers prepared and split their knowledge base, which allowed for innovative design regarding creative challenges. Inversely, engineers opted for rule-based design, in which convergent knowledge base was applied. Regarding the relationship between constraint and creativity, Arrighi et al. (2015a) revealed two competing ideas; industrial constraints may decrease the degree of creativity, but at the same time increase the awareness of fixations and thereby the capacity of originality. Agogué et al. (2015) provided more evidence that engineers and industrial designers have different creative behaviours. In their experiment, industrial designer students performed better in idea-generation with regards to both fluency and originality, because they were less fixated on one aspect than engineering students. They further indicated that the creative capabilities of individuals in both groups were constrained due to the introduction of an uncreative example that reinforced the fixation effect. This is in line with their previous findings (Agogué et al. 2014).

The main purpose of this study is to identify how designers and engineers approach the prototyping process and what their involvement at different stages of new product development is. To gain deeper insights into the specific dynamics of a prototyping process, a two-stage model was chosen to collect data. In the first stage, interviews with relevant company representatives were conducted to gain a deeper understanding of the prototyping process and the rationale behind the prototyping activities. The results of this stage also helped to design the second stage, which was a prototyping workshop with different discipline groups, including engineering students, interaction design students, and innovation management students. Here the focus was on the practical prototyping achievements at the early phase of prototyping process. The workshop contained two different experimental setups, with a technical-oriented convergent challenge and an open-ended divergent challenge, respectively. Based on the findings of from our interviews and the previous discussions, we assumed in the second stage experiment that engineering students would have the best performance in the first experiment, as defined by a more efficient workflow, better use of materials, and a functioning solution. However, in the second experiment our proposition was that the other groups would outperform engineers due to the creative nature of the challenge that the use of various and unfamiliar materials for prototyping, a split the knowledge base (Le Masson et al., 2016), and deliverable solutions for ‘uncertain’ objectives.

**Research design**

In the first stage of data collection, the interviews were based on a semi-structured questionnaire. The questions were developed following the guidelines laid out by Galletta (2013). The protocol contained three parts: introduction; prototyping process, activities, and tools; and roles of designers and engineers. The questionnaires mainly covered the following topics: NPD process, prototyping tools, process and activities, testing process and activities, and involvement of engineers and designers in the process.

We conducted six semi-structured in-depth interviews with CEOs, co-founders, R&D managers, engineers, and designers from Danish small and medium-sized enterprises (SMEs) (see table 1). We choose these SMEs for this study because their NPDs were at different stages and the company representatives had knowledge of the complete prototyping process. Moreover, SMEs make up the
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majority of companies (European Commission, 2012), and face significant challenges in NPD, which made them ideal for the interests of our study.

Table 1

All the interviews took place in meeting rooms at the companies and were audio taped with permission. One of the interviews lasted 25 minutes, and the rest lasted approximately 40 minutes. In addition, we have follow-up interviews with two of the companies because they had made additional progress in their NPD. The follow up interviews lasted around 30 minutes each.

Based on the findings from the interviews, a prototyping workshop was designed to compare certain aspects of prototyping activities and processes between engineers and designers. These aspects included use of materials, workflow, and use of prototypes. In order to have similar groups of participants and avoid possible confounding factors, we defined inclusion and exclusion criteria for recruitment participants. They were:

• Participants should have an educational background in either engineering or design
• Participants should be at the same professional level and have experience in prototyping
• The ages of participants should be in the same range (20 to 30 years for this study).
• Participants should not have direct experience in our specific study tasks.
• The participants should have no significant difference in culture background in terms of taboos, religions, or traditions.

These criteria could ensure that the participants had the same level of professional experience, and avoid unnecessary hierarchy due to the difference of age and experience. These criteria also allowed us to avoid any influence on the study of prototyping behaviours due to social issues that may appear due to differences in taboos, traditions, or major culture differences.

For the workshop, nine students from different study programmes at the University of Southern Denmark were invited. They all met the criteria and were divided into three groups according to their study programmes.

• Three Mechatronics students, third year undergraduate (“Engineers”)
• Three Interaction Design students, third year undergraduate (“Interaction Designers”)
• Three Innovation and Business students, third year undergraduate (“Innovation Managers”)

All the students were from engineering programmes with a focus on different areas of study. Mechatronics is a traditional engineering programme that covers both mechanics and electronics. (hereafter referred to as engineers.) Interaction Design is a design engineering programme that contains fundamental engineering topics and a focus on industrial design and user interaction. (hereafter referred to as interaction designers) Similarly, Innovation and Business is an innovation engineering programme where students have to learn innovation topics (such as innovation management, business models and entrepreneurship) in addition to the core engineering topics (hereafter referred to as innovation managers). In this scheme, we could ensure the participants had a common understanding of prototyping, but could still distinguish the groups based on different backgrounds. All participants had prototyping experience and were familiar with team work.

The workshop consisted of two challenges:

1. Egg drop challenge. Each group was asked to develop a prototype that could prevent an egg from breaking when it was dropped from a high place.
2. New use of old phones. Each group was asked to develop a prototype that could give new life to an old smartphone by turning it into a toy for kids.

The first challenge had been presented by Agogué et al. (2015) in a creativity study, in which the purpose was for ideation, i.e. to generate as many and innovative ideas as possible. We used this exercise as a technical-oriented challenge, aimed at a specific solution. The use of the prototype was to test functionality, i.e. preventing an egg from being broken when dropped. There was not much room for interpretation. We choose this challenge because it did not require any specific engineering skills, so all three groups could work on it, and it could be done within a reasonable amount time allotted for developing a low-fidelity prototype. The second challenge was open-ended, with the focus on a scenario and interaction, rather than implementation of a specific function. This challenge had more room for creativity, interpretation, and reflections.

Forty minutes were given for each challenge. The dropping test was conducted after the first challenge, and for the second challenge, we allowed ten minutes for each group to present their prototype as well as to explain the concept behind it.

A broad range of materials was given to the participants, and the different groups had the same prototyping materials. To analyse the workshop, we took video recordings with permission. Additionally, a questionnaire was answered by each group at the end of the workshop to investigate the processes, activities, and methods of prototyping.

Results

Interview findings

Interviewee A focused on the early phase of prototyping. He expressed clearly the independent roles of designers and engineers in the prototyping process. He believed that industrial designers provide the overall drawing of the product idea first, which does not take all the necessary details of the prototype into account. Then the engineers take it over and produce a set of CAD drawings for the first working prototype. The engineers and the designer create a tangible prototype together, which they will analyse with each stakeholder involved in order to detect early phase problems.

Interviewee B expressed that customers were involved at the beginning of the product development process, since each product was designed towards the customers’ individual demand. He showed two cases of the prototyping process. Firstly, customers bring a semi-finished prototype, and require redesign for manufacturing, i.e. optimizing the prototype design in order to simplify the manufacturing process and reduce the cost. In another case, customers have demands only. Engineers need to create ideas together with the customers, and further build the prototypes. In this situation, the prototype often passes through multiple iterations to reach a prototype for the final product specification and the certification requirements when needed. Only engineers are involved in the prototyping process in collaboration with the users.

Company C is in a consuming market, in which the life cycle of consuming products is normally short. As the interviewee mentioned, “Dedicated to relentless innovation” is the motto of their company. They have NPD stakeholder meetings twice a year, in which they select the sketches of ideas that designers bring in. Selected ones go through a market evaluation process, and then a preliminary prototype of the focused idea will be created. A professional testing team is employed to give feedback. After a maximum of five iteration rounds of redesign and test, a ready to produce prototype will be delivered to manufacturing.

Company D is a start-up that was founded less than a year ago by a group of engineers. The interview was focused on one of their products, which is currently in manufacturing and will be launched to the market soon. From initially hearing the idea to a generating final product, they have developed eight prototypes. For the first five prototypes, the purpose was shifting from a feasibility test of the technology to the proof of concept, with the initial shape of the product appearing. Afterwards, they teamed up with a designer for a study of ergonomics and user experience. A prototype was originally developed with what they thought was an acceptable design. However, when moving to the next phase, the design had to be changed significantly in order to satisfy the product specification as well as the manufacturing requirements. They got help from external partners – structural engineering professionals – to refine and finalize the prototype and make it ready for production. Over the whole process, a designer was mainly involved in the ergonomics study, but as the interviewees mentioned, “Although we are engineers, we also have design experience and skills, and we do follow design thinking when prototyping. [...] The role of either a designer or an engineer in the process was not very clear in our company, since we are a small team, (in which) people have multiple roles.”

Interviewee E is an engineer in a small company. He demonstrated a project that was accomplished recently. The project started from idea generation and moved to a working prototype that had been delivered to the end user. Since there is no further step for manufacturing, the process stopped before the final phase prototyping. As the engineer mentioned, the goal was to provide a working prototype to the end user. Feasibility testing and realizing the functionality were their foci. Preliminary prototypes were developed for feasibility testing of the technology, and then they developed a proof of concept prototype and tested it together with the end user. After improving the features and refinement steps, the working prototype was finally delivered to the end user.

Interviewee F is a designer and a co-founder of a start-up company. Together with some engineers, they developed a novel electronic system that could enhance the service provided by certain organizations. The designer expressed that their process crossed three main stages: a very quick early phase of prototyping to demonstrate the concept, a technology-focused middle phase for proof of concept, and a redesign phase for the final product. They started with a number of sketches and tangible mock-ups for showing their concept. At the initiation, they were also motivated to join an entrepreneur competition, in which LEGO bricks were used to create a scenario that people can interact with. By doing the early phase mock-ups, they not only got positive feedback from the potential users about the concept, but also received valuable suggestions to refine the idea, before they spent real effort on prototyping. Then the focus was shifted to the technical challenges, and the engineers attempted to realize the whole and detailed setup of the system immediately. With this mind-set, they did not follow the suggestion by the designer of using simple technology like Arduino to test the features. It ended up with a complicated system based on “fancy technology”. The system
became very difficult to test in real-world settings. “This attempt was a failure,” as the designer expressed, “we noticed it won’t work at very late point after such a lot of efforts. We had to make serious decisions to either continue the project or close it up. The engineers learned from it, and followed my suggestion of using Arduino for testing some features first.” A number of prototypes were developed step by step to reach the final one for manufacturing. On the way, they had to consider manufacturing, i.e. using injection for casing, and implement it in the prototyping process.

Table 2

Table 2 lists the responses to the prototyping process and activities from each company. In the early phase of prototyping, companies A, C, and F had sketching activities by their designers, while companies D and E, in which mainly engineers were steering the process, started with preliminary prototypes right after ideation. “It seems that the engineers have the mind set to go to the details immediately”, the designer from company F mentioned. In the middle phase, most of the companies had the work done in collaboration between the two disciplines, and the prototype underwent tests for both functionality and user experience. In the final phase, when the prototype was refined for manufacturing, mainly engineers played an essential role in the process. As the interviewees from company D mentioned, “The structural engineers, whom we collaborate with, have the knowledge that we don’t have, which is significantly important when we sent our final design for manufacturing. They are experts for such engineering skills.” The managers from the SEMs were actually expecting that designers and engineers could use the “right” prototypes at the “right” moment. But it seems that the SMEs are missing a doctrine or guideline to support the management of this process. Moreover, all the companies benefitted from rapid prototyping technology, including CAD tools and 3D printers, regardless of whether these were used by a designer or an engineer. Interviewees D, E, and F also addressed the usefulness of simple tools such as Arduino in the early phase of prototyping. As the designer expressed, “The prototyping process has gotten easier throughout the years thanks to the advent of new technologies like Arduino that makes the action of prototyping less complicated than before, especially for the early stages of the product development. [...] to use these kinds of tools saves time and resources [...]. Because they are easy to use, it will be possible to involve different stakeholders in the prototyping process.” He further stated, “It seems that the engineers were more reluctant to use simple prototyping tools some years ago, but now they are more open to them.”

Prototyping workshop

Challenge 1: Egg dropping challenge
The engineers conducted prototyping in a structured way. They started with analysing the available materials and the resources, and then worked on idea generation of how the prototype should work, taking into consideration the available materials. Although there was time reserved for the sketching process, they skipped it without any discussion in the group. Instead, they all conveyed their preferred ideas and agreed on the one to work towards. The task was divided and parts assigned to each member, and then they started prototyping right away. A pre-test was conducted before the final feasibility test. They had confidence in their first prototype, since they did not leave much time
The interaction designers sketched out different ideas on paper individually. Then they had a relatively long discussion in order to investigate all different ideas. During this part they also checked the available materials, and analysed what would fit the task best. Very simple prototypes were developed in a short period of time and tested out. After breaking an egg, they reassessed their idea and developed a prototype that was different from the other groups. This prototype was successful in the feasibility test, and the materials were used efficiently.

The innovation managers also started with paper sketching individually. After a short discussion, they agreed on the focused feature to implement. While checking and collecting the materials, they had another idea and decided to go for it. Then a prototype was built. Since there was still time available, they decided to implement another feature into the prototype. No pre-test was conducted for the first prototype. They also succeeded in this challenge, but the use of materials was redundant.

**Challenge 2: New use of old phones**

The engineers seemed to get lost in this challenge. Without a clearly defined technical challenge to overcome, there was a lack of motivation and creativity to come up with any idea themselves. With help from the facilitator, they focused on a certain feature of the smartphone and tried to enhance it in a prototype. The final prototype was mediocre in the execution and did not meet their expected specification. This led to a poor presentation.

Similar to the first challenge, the interaction designers sketched several ideas on paper individually, and then followed up with a relatively long discussion, which identified the primary features and what the prototype should look like. A prototype was developed that combined different smartphones in order to encourage the kids to play together rather than isolating them as smartphones normally do. In addition, they also developed a scenario to demonstrate how kids would play with it.

The innovation managers in this group sketched many different ideas on paper. According to the available materials, they agreed on an idea that was feasible to prototype. A low fidelity prototype as an accessory to smartphones was developed, which could not only show the idea but also demonstrate the function.

Figure 6 demonstrates the examples of prototypes that were developed in the workshop for the two challenges. The left image shows the structure for egg drop challenge, where the egg was attached in the centre. The right one shows the prototype based on Lego bricks that enhanced the camera with new features of selective lenses.
Prototyping process

Table 3 lists the summarised prototyping processes of each group. Consistent with the data from the interviews, the engineers group did not consider sketching part of the process. They focused on the specifications in the task, and came to the details when developing the prototype. They had a linear process in this early phase, with the clear goal of testing the feature. The interaction designers spent time on sketches and mock-ups to test ideas at a very early phase. They were the only group to use an egg for a pre-test. Compared to the engineers, their process was non-linear, with several small loops for different tests, including (but not limited to) feature tests. They spent more effort on the early phase testing. Innovation managers also did sketching to show and test out different ideas, but no pre-test of the prototype, instead choosing to spend their time on improving it to secure a success.

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The prototyping processes of each group for the second challenge are listed in Table 4. The engineers performed very differently from the interaction designers and innovation managers. They struggled with identifying the problem, since the challenge was not defined as clearly as a technical task. This implies that engineers, who are trained for problem solving, may be less familiar with prototyping for testing the concept in the early phase. It seems that for engineers the ‘real’ purpose of prototyping should be to work towards a technical challenge that needs to be overcome. This challenge was not serious enough for them to proceed. Both interaction designers and innovation managers had smooth performances in this challenge. Their processes were similar, though designers focused more on the interaction part in a ‘real’ scenario while industrial engineers provided a low fidelity, but functioning, prototype. Furthermore, both groups used Lego bricks for prototyping, as one participant underscored “how difficult it is to not choose Lego when it is available, especially for this kind of low fidelity prototyping”. |

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Table 5 lists the main differences and similarities between the two roles based on the results from both the interviews and the experiments. We can see that the prototyping processes and activities between engineers and designers are very different, especially in the early phase, but become more similar in the middle and final phases. The results from the experiments are in line with the results from the empirical study (early phase) regarding prototyping activities and use of prototype. In addition, the roles of designer and engineers become less clear as the design process progresses. The barrier between the disciplines is decreasing along with the emergence of new technologies, tools, and materials for prototyping.

Table 5

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<td>Engineers and Designers have very different prototyping processes and activities. Engineers focus on technical challenges, while designers focus on interaction design. Both use Lego bricks for prototyping. The barrier between the disciplines is decreasing as design processes become more integrated.</td>
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Table 5 lists the main differences and similarities between the two roles based on the results from both the interviews and the experiments. We can see that the prototyping processes and activities between engineers and designers are very different, especially in the early phase, but become more similar in the middle and final phases. The results from the experiments are in line with the results from the empirical study (early phase) regarding prototyping activities and use of prototype. In addition, the roles of designer and engineers become less clear as the design process progresses. The barrier between the disciplines is decreasing along with the emergence of new technologies, tools, and materials for prototyping.

Table 5
Discussion and Implications

This paper presents the prototyping process and activities from the perspectives of engineers and designers as well as explores their involvement at different stages of NPD. The study was conducted based on semi-structured in-depth interviews and a prototyping workshop. A number of articles have described the prototyping processes in each discipline, but no studies have compared the processes and activities between engineers and designers.

Several studies have shown the positive effects of integration of design in NPD on companies’ corporate identity, brand, and financial performance (Beverland, 2005; Ravasi and Stigliani, 2012). Roper et al. (2016) provided more evidence to support this benefit with a systematic quantitative analysis of Irish manufacturing plants. Their results showed that continuous involvement of designers in NPD in large companies could provide better performance than only employing designers in some NPD stages or certain activities. The collaboration between designers and other functional groups was significantly important. This is in line with our findings that many of the prototyping activities are heavily based on cross-disciplinary collaboration. Our study did not investigate the effectiveness of design in NPD. We focused on the prototyping process and activities as part of the NPD process instead. The NPD processes expressed by most of the interviewees were to a certain extent following the stage gate model (Cooper, 1993). Some interviewees were more familiar with the model than others. When the questions moved to the prototyping process and activities, which could be seen as a stage of NPD process, the answers become less consistent. The understanding of the interviewees was that prototyping happened at different stages in the product development process. In order to get a clear overview, we planned to apply Exner’s prototyping process model and categorize the interviews according to the three phases, namely, 1st-Clarification of the task, 2nd-Conception of the idea, and 3rd-Design of the concept (Exner et al., 2015). However, the model did not seem applicable in this case and likely would not have distinguished the interviews. Both the first and the second phases are at the very early stage in the prototyping process, and the interviewees who described the early stage prototyping covered both phases. The third phase covers the process from the first prototype to the final prototype for production, which could be a long process including many prototypes with different testing purposes. Many of the interviewees described the third phase, but their answers could be further categorized. Based on the findings from the qualitative study (see table 2), we introduced a new model that categorizes the prototyping process into another three phases (see figure 7). Early phase prototyping includes from generating an idea to building preliminary prototypes, mainly testing the concept or technology. This phase covers the first and second phases of Exner’s model, i.e. clarification of the task and conception of the idea. For the third phase (design of the concept), we further broke it down and categorized it as middle phase prototyping and final phase prototyping. The middle phase is used to realize the features for proof of concept, and in the final phase, prototypes should meet the product specifications needed to be ready for manufacturing. Responses from the interviewees were different, in which some covered all of the prototyping phases, while others covered one or two phases.

Exner’s model is more suitable for analysis of the second part of our study, the prototyping workshop. Early phase prototyping process, including first phase and second phase (see figure 5), were presented at the beginning of the workshop, with the intention to create a common understanding
level among all the participants. Materials for sketching and for developing preliminary prototypes were prepared and available during the entire workshop. Since in the prototyping workshop it was only feasible to test the early phase prototyping, the results were used to analyse the prototyping process and activities in this phase.

The findings of the empirical study have shown how a prototype can be used for different activities. The results indicate that designers underscored the importance of a tangible prototype in the early stages of NPD in order to show how an ideal product is going to be (Buchenau and Suri, 2000), not only so they can get feedback but also to build interest around the idea. In later stages both engineers and designers used prototypes to analyse functions, for proof of concept, to gather feedback from the user, and to evaluate how the user experience was going to be (Buchenau and Suri, 2000). Considering the three-dimensional spaces model, described by Houde and Hill (1997), our results indicated that the focus shifts throughout the prototyping process. In the early phase, when a rough prototype was built, the “role” was the main focus and was one of the main interests of designers, since they wanted to investigate a design space in order to identify useful functions for the ideal product. “Implementation” was an important aspect immediately after the early phase, when the functions were identified and had to be implemented in a prototype. This aspect was more interesting to engineers since they were more involved in this process. Meanwhile, the “look and feel” was also important in this phase. The designers could identify the main components important to the user experience. In the final phase, engineers played a bigger role again. They redesigned the prototype in order to meet the manufacturing requirements or for optimization. This part could not be represented by the three-dimensional space model.

The results suggest that designers are more willing to develop low fidelity prototypes than engineers. These could be used for different purposes, such as investigating the design space (Virzi, 1989) when the necessary features are not yet identified and have to be researched, involving the users in the process (Muller, 1991), which designers express as one of the most important aspects in the beginning of the NPD because it can give interesting insights, and provoking innovation (Wulff et al. 1990) due to the involvement of the user, and opening up the possibility to re-think the prototype. Engineers are more willing to spend efforts on the high fidelity prototypes, which have the advantage of allowing for the possibility to demonstrate the implemented features and the potential uses (Rudd et al., 1996) in addition to the possibility of convincing other stakeholders about the qualities of the product (Berghel, 1994). The findings also indicate that engineers and designers have different perspectives on the purpose of a prototype. This can be directly linked to the goals of a prototype as suggested by Lichter et al. (1993). The designers prefer to spend more efforts on “exploratory prototyping”, especially in the early phase, when they want to develop rough prototypes that give the possibility to explore different situations in the design space. Engineers like to target “experimental prototyping” in the middle and final phases, when the requirements are already identified and needed to be tested in a real context with the user. Designers also work on “experimental prototyping”. When applying the framework proposed by Lim et al. (2008), the data reveals that designers used prototypes both as filters and manifestations, but engineers focused more on manifestation. These efforts describe prototyping mainly from the designers’ perspective. This study provides a good complement to the understanding of prototyping from an engineering perspective, as well as a comparison of the two domains. Yasar (2007) described the different uses of prototypes depending on who is going to adopt it, designers, engineers, or users. Designers use
prototypes to identify the functionalities and requirements, while engineers test the effectiveness of them. Lastly, the users provide a better understanding of the system of usefulness and functionalities. Comparing to Yasar’s descriptions, our study provides an overview of prototyping process including, but not limited to, the use of prototypes. Furthermore, the roles of designers, engineers, and users are not as clear as Yasar (2007) described. In addition to those descriptions, we found that designers also have interests in user experience studies and take them into consideration in prototype development; in this case, users, instead of testing the prototype at the end, get involved earlier. Depending on the situation, engineers are also able to identify the requirements and are active in this stage, and not just in realizing functions. These findings are in line with the studies on lead-user studies (Bilgram et al. 2008; Gerhard et al. 2008; Brem and Bilgram, 2015) and collaborative prototyping, which are useful in understanding the customers’ needs (Bogers and Horst, 2014). Implementing front-loading innovation processes can lower the time and cost spent on prototyping and experimentation (Thomke and Fujimoto, 2000). If the requirements demanded by the user are identified from the very beginning there will be less wasted time in the later stages, and also fewer errors (Yeomans et al., 2006). The results from the workshop suggest our assumption that engineers performed better at the technical-oriented convergent task but were outperformed in the second challenge with the open-ended divergent task. Since all groups had the same materials for prototyping, it underlines that engineers were missing knowledge on the different types of prototyping. It further indicates that they had a conservative attitude towards the variety of prototyping materials that are not on the “traditional list”. Innovation managers were knowledgeable about the variety types of prototyping, but missing certain training. Interaction designers followed a kind of contingency approach, and had the ability to identify the validity domain for the right type of prototype.

Based on the findings from the interviews and our experiment, we summarize the prototyping process and activities in a three-phase model. It has similarities to Exner’s model (2015) in terms of three phases with different objectives and activities. Exner’s model (2015) was derived over a two-day workshop with more focus on the early stage of prototyping. Our model categorized the phases differently, which is suitable for describing both short term and long term prototyping development processes. As shown in figure 7, at the early phase, the inputs to the model are ideas, which can be sketched, normally by designers, and then built into a mock-up. The main purpose at this stage is testing the concept. Once the first prototype has been developed and tested, it moves to the middle phase. Realizing and testing the features are the foci, which normally require engineering skills (depending on the specific domain). In the final phase, the focus moves to building a functioning prototype. The target was to make it ready for manufacturing, including testing the stability and reliability. The main concept and technology would not be changed in this phase, but due to the requirements for production, a prototype may require a totally design revision. The process can be linear from early phase to final phase, but very often it is iterative. This is in line with the typology proposed by Thomke (Thomke, 1998; Thomke, 2003; Thomke and Fujimoto, 2000) that product development process can be represented by a numerous problem-solving cycles. Each of them consists of Iterative Four-Step Learning activities, i.e. design, build, run, and analysis. Our model also extends this framework so that the purposes and uses of different types of prototype at different stages are more explicitly described.
In addition, our findings indicate that the level of fidelity does not necessarily increase continuously from low to high throughout the whole process. For example, a high fidelity prototype may have been developed in the process, but a new prototype may need to be developed again from sketches due to testing feedback or the requirements from manufacturing. This was not demonstrated by Exner’s model (2015). Furthermore, our model also addresses the important prototyping activities regarding manufacturing, which were not well considered in the previous literature.

Figure 7

Limitations and further research
There are also limitations to this study. Although the interviewees were carefully selected as the focus group, the number of interviewees was low, and cannot provide the whole image of prototyping procedure from the industry. Large size companies may have different approaches compared to SMEs and start-ups, e.g. the possible missing of a doctrine to support when to use the right type of prototype may link to the size, experience, and resource of the companies. This should be investigated. Future studies in different cultural contexts may also shed light on the intercultural aspects that we could not address in our study. In addition, if and how companies apply design thinking could also be of interest for future studies. Finally, longitudinal studies would foster our understanding on developments over time, such as the impact of specific training methods.

The participants in the workshop were students, who were close to finishing their studies. Their performances are most likely different from experienced engineers and designers with many years of work experience in a company. Furthermore, the workshop was based on a small number of participants. Therefore, the goal of this paper is not to express the absolute similarities and differences between engineers and designers on prototyping. Instead, it is a preliminary study that created an improved and complementary understanding of prototyping. Based on that, future research may replicate the study design to further shed light on this phenomenon.

This study described the differences and similarities in prototyping processes and activities between engineers and designers. How to enhance the collaboration across disciplines and increase the prototyping efficiency within the overall process were not described in this paper. A prototyping process model has been derived that could explain the current general prototyping process. Important parameters, such as tools, materials, cost, and time could be considered in the model. To fully address these aspects requires further studies. Finally, we recommend longitudinal studies that cover at least a two year period. In such a context, the results will be much more stable, and the individual development of participants could also be reflected.

References


The final version is available at https://doi.org/10.1111/caim.12242”

Figure 1. General prototyping process (Walfel, 2009, p. 30)

76x66mm (251 x 251 DPI)
Figure 2. A modified Four-Stage Model of the design process (Löfqvist, 2010, p. 412)

134x242mm (96 x 96 DPI)
Figure 3. Generic design thinking process (Geissdoerfer et al. 2016, p. 1221)

360x165mm (96 x 96 DPI)
Figure 4. Design – Space – Value – Management model (Hatchuel et al. 2005, p. 349)

340x104mm (96 x 96 DPI)
Figure 5. Prototyping process (Exner et al., 2015)
Figure 6. Examples of prototypes developed for egg dropping challenge (left) and new use of old phone challenge (right).

220x177mm (96 x 96 DPI)
Figure 7. Three-phase prototyping process and activity model

250x173mm (150 x 150 DPI)
<table>
<thead>
<tr>
<th>ID</th>
<th>Industry</th>
<th>Size</th>
<th>Market</th>
<th>Interviewee</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Machine tools</td>
<td>Small</td>
<td>B2B</td>
<td>CEO</td>
</tr>
<tr>
<td>B</td>
<td>Electronic Manufacturing Services</td>
<td>Medium</td>
<td>B2B</td>
<td>CEO</td>
</tr>
<tr>
<td>C</td>
<td>Sport equipment</td>
<td>Medium</td>
<td>B2C</td>
<td>R&amp;D manager</td>
</tr>
<tr>
<td>D</td>
<td>Electronic devices</td>
<td>Start-up</td>
<td>B2B/C</td>
<td>CTO &amp; COO</td>
</tr>
<tr>
<td>E</td>
<td>Electronic devices</td>
<td>Small</td>
<td>B2C</td>
<td>Engineer</td>
</tr>
<tr>
<td>F</td>
<td>Electronic devices</td>
<td>Start-up</td>
<td>B2B/C</td>
<td>Designer</td>
</tr>
</tbody>
</table>
Table 2: Simplified prototyping process and activities of each company

<table>
<thead>
<tr>
<th>ID</th>
<th>Prototyping phase</th>
<th>Prototyping Process and activities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EP</td>
<td>MP</td>
</tr>
<tr>
<td>A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>C</td>
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<td>X</td>
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<tr>
<td>D</td>
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<td>X</td>
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<tr>
<td>E</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Note: EP, MP, and FP represent early phase, middle phase, and final phase, respectively. D, E, M, U, and T represent designers, engineers, management board, users, and testing team, respectively. These processes are simplified, and do not represent the iterations in the prototyping process. In practice, iterations should be considered.
<table>
<thead>
<tr>
<th>Groups</th>
<th>Prototyping Process and activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resource analysis – requirements identification – ideation and selection – prototype development – pre-test – (small) prototype refinement</td>
</tr>
<tr>
<td>2</td>
<td>Sketching – resource analysis – mock-ups development – pre-tests – recreate the idea – prototype development</td>
</tr>
<tr>
<td>3</td>
<td>Sketching – idea selection – resource analysis – recreate the idea – prototype development – prototype improvement</td>
</tr>
</tbody>
</table>
Table 4: Challenge 2 — Prototyping process of each group

<table>
<thead>
<tr>
<th>Groups</th>
<th>Prototyping Process and activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Clarify the problem with help from the facilitator – identify the idea to proceed – prototype development</td>
</tr>
<tr>
<td>2</td>
<td>Clarify the problem – sketching – idea selection and refinement – prototype development – demonstration in created scenario</td>
</tr>
<tr>
<td>3</td>
<td>Clarify the problem – sketching – resource analysis – idea selection – prototype development</td>
</tr>
<tr>
<td>Differences between engineers and (industrial and interaction) designers</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Prototyping process</strong></td>
<td>Engineers had a more linear prototyping process with certain milestones where specific goals had to be reached in order to push the process forward.</td>
</tr>
<tr>
<td></td>
<td>Designers followed a kind of contingency approach, with small loops to test out ideas quickly.</td>
</tr>
<tr>
<td><strong>Prototyping activities</strong></td>
<td>Compared to engineers, designers were more open to the variety of prototyping materials and tools, especially for low fidelity prototypes. For instance, sketches were not an option to most engineers.</td>
</tr>
<tr>
<td><strong>Use of prototype</strong></td>
<td>Engineers seemed to use prototypes mainly for testing the features and functions.</td>
</tr>
<tr>
<td></td>
<td>Designers preferred to investigate the design space in order to find new possibilities.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Similarities between engineers and (industrial and interaction) designers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prototyping process</strong></td>
</tr>
<tr>
<td><strong>Prototyping activities</strong></td>
</tr>
<tr>
<td><strong>Users’ role</strong></td>
</tr>
</tbody>
</table>