DTU Mechanical Engineering
Department of Mechanical Engineering

# Design by Prototyping in Hardware Start-ups

Lasse Skovgaard Jensen

PhD Thesis

# Design by Prototyping in Hardware Start-ups

PhD Thesis


Lasse Skovgaard Jensen
October 2018

DTU Mechanical Engineering
Department of Mechanical Engineering

# Design by Prototyping in Hardware Start-ups

PhD Thesis, October 2018
Lasse Skovgaard Jensen, PhD Student
Section of Engineering Design & Product Development
DTU Skylab & Department of Mechanical Engineering
Technical University of Denmark

Academic Supervisor
Ali Gürcan Özkil, Associate Professor, PhD
Section of Engineering Design & Product Development
Department of Mechanical Engineering
Technical University of Denmark

Academic Co-Supervisor
Niels Henrik Mortensen, Professor, PhD, Head of Section
Section of Engineering Design & Product Development
Department of Mechanical Engineering
Technical University of Denmark

Collaboration Partner
Mikkel Sørensen, Head of DTU Skylab
Department of Innovation & Sector Services
Technical University of Denmark

Department of Mechanical Engineering
Section of Engineering Design and Product Development
Technical University of Denmark (DTU)
Nils Koppels Allé Building 404
2800 Kgs. Lyngby
Denmark

Phone (+45) 45256263
www.mek.dtu.dk
www.skylab.dtu.dk

# Abstract

This PhD thesis focuses on physical prototyping in hardware start-ups that develop consumer products, and is conducted within the field of engineering design research.

Prototyping is not a new thing in product development, but to effectively make use of prototypes throughout the development process is a complex and interwoven challenge for designers. Emerging desktop digital fabrication tools for prototyping and increased globalization are contributors to this complexity, and the designer's role in product development is getting more omniscient. Surprisingly, researchers have identified that despite its importance, prototyping is currently one of the least understood aspects of product development.

In this light this project has three objectives; The first is to expand the existing understanding of product development in hardware start-ups, and provide a particular focus on prototyping. Second, the project investigates how digital fabrication tools can be applied to collect feedback from users in the early stages of product development. Finally, as the third objective, the project provides a holistic prototyping framework, the Prototyping Planner. The objective is, that the framework can support novice designers in better comprehending opportunities in prototyping.

The project has been conducted as a collaboration between DTU Skylab and DTU Mechanical Engineering. In addition to the academic contributions, a central motivation for the project is to support the growing population of young entrepreneurs, who are dedicated to develop new hardware products for the benefit of society.

The first objective, focused at understanding design in hardware start-ups, is assessed through studying the existing body of literature. This provides an overview of how prototypes are defined, and what different roles and purposes of prototypes have been described. With offset in insights obtained from literature, we use both qualitative and quantitative research methods to further develop our understanding of prototyping activities, and also the product development challenges that hinders success of hardware start-ups.

The second objective, explores how digital fabrication tools can be utilized for prototyping activities with test users. Through two studies conducted with hardware-start-ups, we propose respectively four design heuristics for prototyping with digital fabrication and a seven-step data-driven approach for interlacing the known concept of 'Design of Experiments' and prototyping of hardware products.

Different studies have documented how novice designers are lacking the competencies to fully comprehend the potentials of prototyping. The third objective is hereby approached through the accumulated insights of the project, which supported the conceptualization of the Prototyping Planner. The framework is evaluated though a controlled experiment with 20 design teams working on an identical design challenge. The results reveal that the framework is successful in nurturing 'prototyping mindsets' among the participants, but

also identify a range of opportunities for further improving the framework. Such opportunities are to be seized in future research activities on the topic of prototyping.

# Resumé (in Danish)

Denne PhD afhandling fokuserer på ‘prototyping’ i opstartsvirksomheder der udvikler fysiske forbrugerprodukter, og er placeret indenfor forskningsfeltet konstruktion og produkt-udvikling.

Prototyping er ikke et nyt fænomen i produktvikling, men det at arbejde effektivt med prototyper i en udviklingsproces er en kompleks og dynamisk udfordring for designeren. Der sker en spirende udvikling indenfor digitale fabrikationsværktøjer til prototyping og den øgede globalisering bidrager til kompleksiteten i produktudvikling, hvor der stilles stadigt større krav om alvidenhed hos designeren.

I dette lys har dette projekt tre målsætninger; Den første er at styrke den eksisterende forståelse af produktudvikling i opstartsvirksomheder, her med et særligt fokus på prototyping. Dernæst, undersøger projektet hvordan digitale fabrikationsværktøjer kan anvendes til at indsamle brugerrespons i de tidligere udviklingsstadier af produkt-udviklingsforløbet. Endelig, som den tredje målsætning, bidrager projektet med et holistisk rammeværktøj, ’the Prototyping Planner’. Formålet med rammeværktøjet er at understøtte designere med begrænset erfaring i bedre at forstå og udnytte mulighederne ved prototyping.
Projektet er udført som et samarbejde imellem DTU Skylab og DTU Mekanik. Udover de akademiske bidrag er det en central motivation for projektet at understøtte den voksende population af unge iværksættere, der er dedikerede til at udvikle nye forbrugerprodukter til gavn for samfundet.

Den første målsætning, som er fokuseret på at forstå produktudvikling i opstartsvirksomheder, tilgås via et studie af den eksisterende litteratur. Dette bidrager med et overblik over hvordan prototyper er defineret, og en forståelse af hvilke roller og formål der er blevet beskrevet for prototyper. Med afsæt i disse indsigter anvender vi både kvalitative og kvantitative forskningsmetoder til yderligere at udvikle vores forståelse af prototype-aktiviteter, samt de produktudviklingsudfordringer der kan hindre succes for hardware start-ups.

Den anden målsætning udforsker, hvordan digitale fabrikationsværktøjer kan anvendes til prototypeaktiviteter med testbrugere. Via to studier, udført i samarbejde med hardware start-ups, foreslår vi henholdsvis fire design heuristikker med henblik på prototyping med digital fabrikation og en syv-trins data-drevet tilgang, der kan sammenflette det kendte koncept ’Design of Experiments’ og prototyping.

Forskellige studier har dokumenteret, hvordan designere med begrænset erfaring mangler kompetencer til fuldt ud at forstå og udnytte mulighederne ved prototyping. Den tredje målsætning for projektet er derfor tilgået via den akkumulerede erfaring fra dette projekt, der anvendes som afsæt til at konceptualisere the Prototyping Planner. Rammeværktøjet er evalueret via et kontrolleret eksperiment med deltagelse af 20 hold af designere, der alle arbejdede på en identisk designopgave. Resultaterne viser at rammeværktøjet succesfuldt kan udvikle prototype-tankesæt iblandt deltagerne, men en række muligheder for forbedring identificeres også. Disse muligheder bør forfølges i kommende forskning indenfor prototyper.

# Preface

For as long as I can remember I have had a passion for things. For understanding how they function, are intended to be used and how they are made. In his book *'The Craftsman'*, Richard Sennett states, *"you can't understand how wine is made simply by drinking lots of it."* In that light it seemed a natural choice for me to study engineering.

Now, this thesis concludes my 3-year research project 'Design by Prototyping in Hardware Start-ups', conducted from 2015 – 2018 at The Technical University of Denmark. The project has been made possible through a collaboration between DTU Skylab and DTU Mechanical Engineering, Section of Engineering Design & Product Development. Here, I have been gifted with good colleagues– previous and current - in both parts of the university organization. Thank you all for interesting discussions and shared experiences, both inside and outside the office!

I would like to thank my academic supervisor, Associate Professor Ali Gürcan Özkil and Collaboration Partner, Head of DTU Skylab Mikkel Sørensen for taking the initiative to make this project a reality, and also for giving me the opportunity to be part of it.

To develop the competences required to conduct research can in many ways be considered an apprenticeship. In that regard; Thank You, again, Associate Professor Ali Gürcan Özkil and Professor Niels Henrik Mortensen for your support, guidance and not least patience, whenever I found myself lost or confused.

I would also like to thank everyone who have given of themselves for parts of this project; Collaborating start-up companies, co-authors and all other parties that have taken part in this project. I have experienced nothing but openness and willingness to discuss, collaborate and test ideas.

Just as I have been fortunate to have the privilege to work on this project, I am gifted with a lovely family, good friends and a fantastic girlfriend. Thank you all for your interest in my work, for asking tricky questions, and not least, for your encouragement.

Finally, thank you, to all the entrepreneurial minded and creative students, who make DTU an inspiring and always interesting place.

I have learned a great deal through this project; I hope that you will enjoy reading this thesis, and that you will find it interesting.

Lasse Skovgaard Jensen
Technical University of Denmark
Kgs. Lyngby, Denmark, October 2018.

## Øje og Hånd

**Hvor blir den gode ting til?**
**I øjet og hånden!**
**Den gror af et gensidigt spil**
**mellem stoffet og ånden.**

**Om tingen blir én eller ti**
**eller udspys af løbebånd –**
**Hvis det er en ting af værdi,**
**hvad har den sit udspring i?**
**Øje og hånd.**

**Piet Hein**

## Eye and hand

**Where do good things come true?**
**In the eye and hand!**
**It grows from interaction**
**between artefact and spirit.**

**Whether the thing is one or ten**
**or sprayed out of 'the line' -**
**If it's a valuable thing**
**what has it originated in?**
**Eye and hand.**

**Piet Hein**

---

Pein Hein, 1966
Dedicated Copenhagen wood joiner's guild
Original Poster Design: Bo Bonfils, 1969
Freely translated to English by the author

# List of appended papers

**Paper A**
**Prototypes in engineering design: Definitions and strategies**
Jensen, L.S., Özkil, A.G., Mortensen, N.H., (2016). In: DESIGN 2016 14th International Design Conference.

**Draft IR**
**A study of the roles and purposes of prototypes in 13 hardware start-ups**
Jensen, L.S., Özkil, A.G., (2018). Not submitted for publication

**Paper B**
**Identifying Challenges in Crowdfunded Product Development: A review of Kickstarter Projects**
Jensen, L.S., Özkil, A.G., (2018). In: Design Science Journal

**Paper C**
**Crowdfunded Product Development: A study of hardware start-ups**
Jensen, L.S., Özkil, A.G., (2017). In: Undergoing peer review for journal publication

**Paper D**
**PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT**
Jensen, L.S., Nissen, L., Bilde, N., Özkil, A.G., (2018). In: DESIGN 2018 15th International Design Conference.

**Paper E**
**PROTOTYPING FOR DESIRABILITY BY DESIGN OF EXPERIMENTS: A CASE STUDY OF A HARDWARE START-UP**
Jensen, L.S., Vorting, D., Villadsen, A., Mølleskov, L.H., Özkil, A.G., (2018). In: ASME 2018 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.

**Paper F**
**Fostering Prototyping mindsets: Towards the framework Prototyping Planner**
Jensen, L.S., Özkil, A.G., (2018). In: Submitted for peer review for journal publication

# List of Supplementary Papers

**Paper G**
**MAKERSPACES IN ENGINEERING EDUCATION: A CASE STUDY**
Jensen, L.S., Özkil, A.G., Mougaard, K., (2016). In: ASME 2016 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.

**Paper H**
**Facilitating entrepreneurship in engineering education: Learning in Living Labs across institutional boundaries focusing the role of boundary brokering**
Jensen, L.S., Rasmussen, B., (2018). In: Submitted for peer review for journal publication

**Paper I**
**Assessing Increased Product Line Commonality's Effect on Assembly**
Løkkegaard, M., Mortensen, N.H., Jensen, L.S., Christensen, C.K.F., (2018), In: DESIGN 2018 15$^{th}$ International Design Conference.

**Paper J**
**A music festival as innovative living-lab learning in engineering education**
Jensen, L.S., Rasmussen, B., Marlow, A., Amdrup, N., (2018), in: 46th SEFI Annual Conference, European Society for Engineering Education

# Booklets

**DTU Skylab Guide to Crowdfunding**
Fernvall, P., Jensen, L.S., Bagdonaite, E. (2017),

# Table of Content

# List of Figures

## List of Tables

# 1 Introduction

*This chapter provides an introduction to this PhD thesis, which concludes a three-year research project within the topic of engineering design. More specifically, the project is focused on prototyping activities in hardware start-ups. This first part of the thesis presents an introduction to the topic and its background and problem area. This section is followed by an introduction to the research objectives, the research questions, definition of key terms and finally an outline of the thesis structure.*

---

## 1.1 Background and problem area

This PhD thesis is focused on physical prototyping in hardware start-ups that develop consumer hardware. The empirical foundation of the project is primarily based on hardware start-ups without an existing product portfolio and organizations with limited operating history and resources available. Further, our efforts are mainly focused around the phases of product development taking place before engaging in manufacturing.

In section 1.4 of this thesis we provide an overview of definitions on a range of key terms used throughout this thesis, however it seems appropriate to introduce our understanding of respectively hardware start-ups and prototypes already from the very beginning:
A start-up is a “temporary organization in search of a scalable, repeatable, profitable business model” (Blank, 2012), and hardware start-ups focus on a tangible product, often with mechatronic characteristics. Further, “a prototype is an artefact that approximates a feature (or multiple features) of a product, service or system” (Otto and Wood, 2003), whereas prototyping is referred to as the activity of making and utilizing prototypes in design (Lim et al., 2008).

In the following two sections we provide our perspective on current challenges in the area from the perspective of respectively practitioners and academia.

### 1.1.1 Challenges for Practitioners

Today’s companies compete on a global scale. Development teams are under pressure to deliver innovative products that solve customers’ needs with unprecedented performance through ever faster development cycles. It is estimated that a number in the range of 140 billion US dollars are annually invested in product development activities (Cooper, 2001) and around 40 percent of new products fail in the consumer products and consumer electronics market (Castellion and Markham, 2013).

Products fail for various reasons: they might fail to address the customers’ needs and wants, address a non-existent problem, be poorly designed, be noncompetitive in relation to market dynamics, price or simply fail because of development challenges even before market launch.

To navigate around such potential challenges in product development is a multifaceted process. Over the years, design researchers, who have made it their profession to study and understand the dynamics of product development, have proposed a range of methodologies, methods and tools to support development teams and increase the chances of productive design efforts (Andreasen, 2011). But there are no guarantees for success, and no single approach can accommodate all potential pitfalls that development teams face.

One approach, that has been documented as being of particular importance in enabling innovative outcomes of product development activities, is prototyping (Wall et al., 1992). Studies have documented how prototypes enable development teams to explore concepts, reduce uncertainty, communicate about design, and also obtain detailed understandings of product requirements (Elverum and Welo, 2014;Camburn et al., 2017b). To underline its value, Buur has described how prototyping can be considered 'a way of buying information about a future product' (Buur, 1989). Or, as Tom Kelley, the general manager at the innovation consultancy IDEO, states, 'Prototyping is the shorthand of innovation' (Kelley, 2010).

Despite its potential, prototyping has also historically been associated with major expenses in the development process. Studies document how as much as 50 percent of development costs have been associated with prototyping (Cooper, 2001).

Regardless of prototyping's importance, potential expenses and a productive output, the design research community has focused little on proposing support for prototyping activities. Menold, in her recent dissertation, addressed this discrepancy through the following quote:

*"Engineering design research has failed to provide designers and engineers—practitioners as well as educators—with formal methods or approaches for prototyping … to increase the likelihood of product success. Instead, designers and engineers must rely on experience, tacit knowledge, and individual judgment to navigate prototyping activities, often resulting in the inefficient use of resources and time"*

(Menold, 2017)

We find that at least two recent developments further underline an increasing need for supporting practitioners in their prototyping efforts:

First, the past few years have seen an increasing global interest in entrepreneurship (Acs et al., 2018). As a consequence, increasing numbers of start-up companies are formed. Product development in start-ups is often high in uncertainty and conducted by small teams with little accumulated experience and limited resources. In such a context, prototyping can be of high value. Prototyping competencies have been identified as an underdeveloped competence among novice designers (Lauff et al., 2017). Fortunately, studies have documented that design efforts of novice designers can be elevated through the proper use of support tools (Daalhuizen and Badke-Schaub, 2011).

Second, the recent advancement in digital fabrication tools and associated eco-systems – e.g. the concept of Makerspaces and FabLabs (Jensen et al., 2016) and online design repositories (Özkil, 2017) - have increased the availability of tools for delicate prototype fabrication. While the costs, time allocation and 'barrier of entry' for prototyping in product development are generally lowering as a result, this development also brings new challenges. Wall et al. (1992) made an early observation regarding such desktop manufacturing technologies and argued that consequently the knowledge and skills of fabricators are diminished, which puts the designer in an omniscient position. The logical 'train of thought' seems that this development intensifies the need for supporting designers in their development activities in terms of when, how, and what to prototype.

### 1.1.2 Academic challenges

Prototyping is not a new phenomenon in design research. In fact, the term has existed in literature for decades (Janson and Smith, 1985). Despite historical acknowledgement of its value, prototyping has received little attention as a separate research topic. As stated by Camburn et al. "Prototyping may be simultaneously one of the most important and least formally explored areas of design" (Camburn et al., 2013).

But prototyping is also a multifaceted and integrated design activity that typically has highly contextual characteristics. In their renowned engineering design reference book *Engineering Design*, the authors Pahl and Beitz never reach a conclusion on how to integrate prototypes in the engineering design process. They argue that since "the information they [prototypes] supply may be needed at any point in the design process and so cannot be fitted into any particular slot" (Pahl et al., 2007, p. 113).

As researchers, we are faced with similar challenges today. The existing literature on prototyping seems to be scattered, and there seems to exist no clear overview of how prototypes are defined and utilized in different industries and research traditions (as outlined in appended Paper A).

This could be one of the underlying explanations for why "engineering design research has failed to provide designers and engineers … with formal methods or approaches for prototyping" (Menold, 2017).

A short list of different support tools to assist prototyping does exist today. These tools generally seem to focus on specific subjects like prototype fabrication or particular prototype attributes (Menold et al., 2018). We argue that there seems to be a lack of support for a more holistic interpretation of prototyping, which should focus its metrics on support for designers with limited or intermediate experience in prototyping activities.

As technical universities have started to adopt the concept of Makerspaces and FabLabs, this need for prototyping support is also emerging in our own educational environments. As one of the supplementary papers for this thesis documents, professors evaluate prototyping skills as a central competence to engineers, but are themselves significantly less proficient in delivering education that incorporates prototyping activities (Jensen et al., 2016).

A range of further academic challenges can be identified along the process of providing practitioners with new support tools focused on prototyping:

- The current body of literature does not provide a saturated understanding of how prototypes are utilized in industry (Lauff et al., 2018; Deininger et al., 2017a; Jensen et al., 2017). Such studies can serve as important probes for the identification of best practices and also expand our understanding of the roles and purposes of prototypes in industry.
- In the past few years we have witnessed a growth in technology based start-ups. "Since 2007, the number of start-ups [in USA] has increased 47 percent, from 116,000 firms in 2007 to 171,000 in 2016" (Wu and Atkinson, 2017, p. 20) – some have even categorized this as a hardware revolution (Thornton, 2016); if we are to support these hardware start-ups in their prototyping efforts, we need to better understanding of their specific product development challenges.
- Lastly, as argued by Camburn et al., "The digital age, additive manufacturing, and the emergence of data-driven design will see new approaches and a transformation in what we know today as design prototyping. These emergent trends have been relatively less explored in the research" (Camburn et al., 2017)

In the next section we outline our research context and objectives.

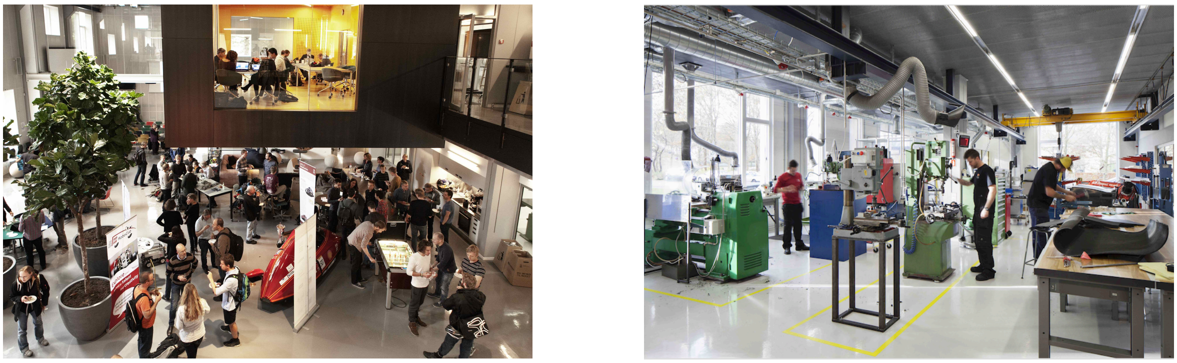
## 1.2 Research Context and objectives

The objective of this research project is to identify, understand and expand our knowledge regarding the product development and prototyping activities in hardware start-ups. Furthermore, the project seeks to provide a framework to support such prototyping activities.

### 1.2.1 Research context

This research project has been funded and conducted as a collaboration between DTU Skylab and DTU Mechanical Engineering.

Entrepreneurship is a central topic in the DTU's strategy (Hempler, 2018). One asset in supporting this strategy is DTU Skylab, a 1550 m2 innovation hub and university Makerspace with a vision to become an 'internationally leading hub for technology-based innovation and entrepreneurship.' DTU Skylab provides access to a range of facilities and support functions, but operates with three focus areas: i) hosting academic courses, ii) supporting industry collaboration and iii) supporting entrepreneurship (Jensen et al., 2016). Figure 1 below provides pictures of, respectively, the open space and the machine workshop at DTU Skylab.



(a) (b)

*Figure 1: Photos from (a) open space at DTU Skylab and (b) machine workshop at DTU Skylab (Photos: Stamers Kontor and Kaare Smith)*

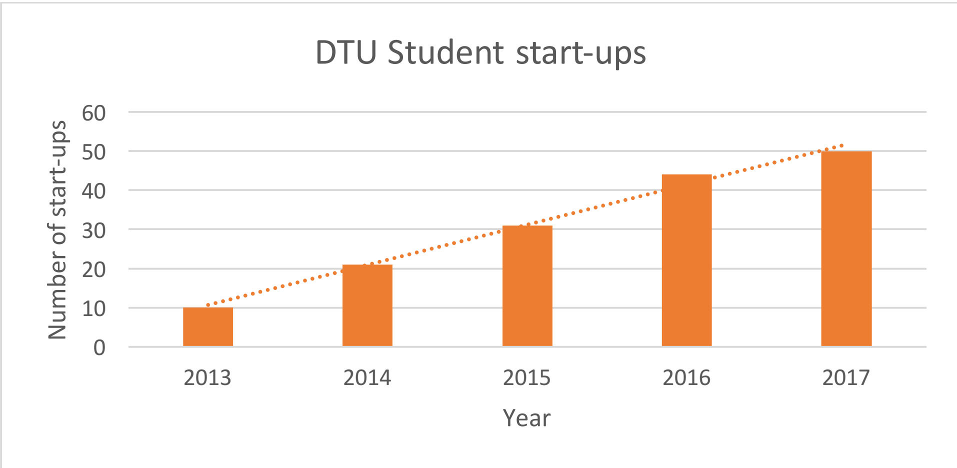



*Figure 2 Overview of student start-ups with VAT numbers at DTU (Pape Thomsen, 2018)*

Over the past few years a quite significant increase in entrepreneurship activities has taken place at DTU, as shown in Figure 2. In the design community we have often differentiated our understanding of designers as, respectively, experts or experienced designers and students. However, this development, in which many young people are pursuing careers as entrepreneurs, increases the numbers of novice-practitioners, and this trend is not specific to DTU - albeit not in all cases with the same momentum (IRIS Group, 2018; Compass, 2015).

The ambitions of DTU to become an international leader in innovation and entrepreneurship require commitment from many stakeholders. This thesis aims to support that overall vision by providing knowledge and insights into the topic of prototyping for designers of limited or intermediate experience. This role hereby feeds into the overall research objectives of this project.

To serve this purpose, different research activities have taken place both inside and outside the university, but with a guiding reminder of delivering results that can be of value to the entrepreneurship community around DTU, especially for those committed to development of hardware products, either as entrepreneurs or through different support functions and educational responsibilities.

### 1.2.2 Research objectives

The objective of this PhD project and its research activities can be outlined in three overall objectives, as shown in Figure 3. Figure 3 further illustrates how the three overall objectives are linked to the appended research studies and the research questions introduced in section 1.3.

The first objective is focused on 'understanding design' (Pahl et al., 2007). In particular, we focus on understanding the processes and challenges of early stage product development in hardware start-ups, and how they use prototypes as a design tool. We study this both from a theoretical and a practical point of view.

The second objective is to 'explore design approaches.' We do this by exploring how emerging digital fabrication tools, such as 3D printers and laser cutters, bring new opportunities in how designers in hardware start-ups can utilize physical prototypes. For this part of the research we explore opportunities and reflect on our results. This is to further develop our understanding of designing and prototyping. We do not formalize concrete support tools for designers though, but rather aim at providing heuristics and guidelines that can be of value to both designers and researchers.

The third objective is to provide support for designers. We seek to do this through a dedicated support framework for prototyping, which draws on the accumulated insights of the project. We intend for the framework to support novice designers in defining, building, testing and reflecting on their prototyping activities.

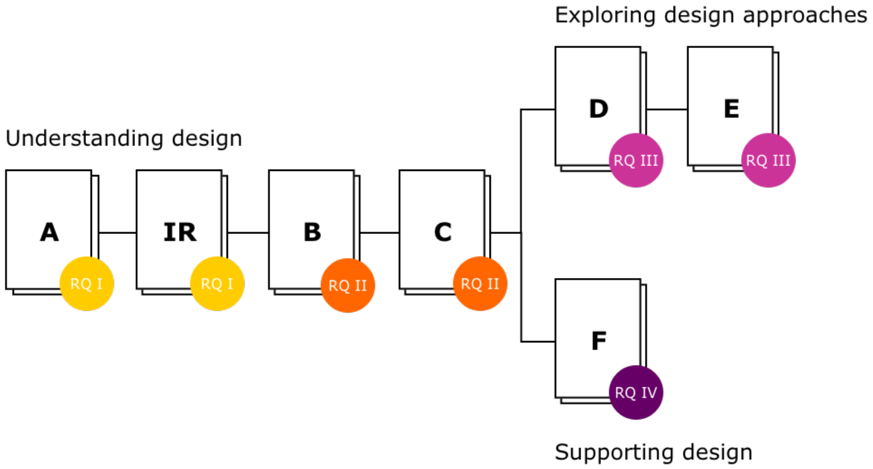



*Figure 3: Research objectives, research questions, appended studies and line of argument of the research project*

## 1.3 Research questions

To guide and structure this project, four research questions were formulated. Collectively they frame the research area and focus, which spans exploratory, descriptive and prescriptive approaches.

The first question is of fundamental nature to the project, as it frames the understanding of how prototypes are defined in the existing literature on engineering design and product development. The question is twofold and concerns the understanding of the role and purpose of prototypes in hardware start-ups.

Research Question I:

- RQI: a) How are prototypes defined in literature and b) what is their role and purposes in hardware start-ups?

We approach the two parts of this question through, respectively, a systematic literature review and through interviews with designers in hardware start-ups.

Our second question concerns the product development challenges that can be identified in hardware start-ups. Our work seeks to understand prototyping activities and how they might possibly be improved. One part hereof is to understand the product development process and the challenges that can potentially be accommodated through design support in prototyping.

Research Question II:

- RQII: What main product development challenges for hardware start-ups can be identified?

This question is approached though an 'empirical review' of start-up teams, who are bringing consumer hardware products to the market through the crowdfunding platform Kickstarter.com. Here we qualitatively assess material documenting the product realization process, which leads us to a range of quantitative insights.

Although prototyping is not a new concept in product development, the past few years have provided vast developments in the tools and infrastructure available for prototype fabrication. This observation leads us to the third research question, which aims to explore how these new fabrication tools might provide new opportunities in approaches to prototyping.

Research Question III:

- RQIII: How can hardware-start-ups make use of digital fabrication technologies in the prototyping of consumer products?

We provide two studies to explore this open-ended question. One focused on understanding how prototypes of different fidelity can affect feedback from users, and a second, where we explore the potentials in adopting the concept of 'Design of Experiments' for dynamically evaluating the desirability of a consumer product.

Our last research question focuses on support for prototyping activities.

Research Question IV:

- RQIV: How can designers, with limited or intermediate product development experience, be supported in their prototyping activities?

We approach this question by proposing a prototyping support framework named the Prototyping Planner. The framework has been conceptualized as part of this project, and we provide an evaluation of the framework in the context of a controlled experiment.

In the following chapter we will outline our research approach. This approach includes further illustrating our line of argument and how the studies conducted contribute to addressing the introduced research questions.

First, we introduce a range of key terms for this thesis.

## 1.4 Definitions of key terms used

The following key terms introduced in Table 1 are used frequently throughout the thesis. A range of these terms can be considered 'slippery terms,' and it should be acknowledged that various definitions exist and are used actively in the literature. One example is how novice designers sometimes are used synonymously with students (Deininger et al., 2017a), and by Ahmed et all. is used to describe engineers with up to five years of professional experience (2003). We have for this thesis adopted the later of the two.

We find that the definitions provided here are suitable for this project and are used consistently throughout this thesis. When no reference is provided, the terms have been defined by the author for the purpose of use in this thesis.

*Table 1: List of key terms and their definition or description*

| **Term or concept** | **Definition or Description** |
|---|---|
| Hardware start-up | A start-up is a "temporary organization in search of a scalable, repeatable, profitable business model" (Blank, 2012).<br>Hardware start-ups focus on a tangible product, often with mechatronic characteristics. |
| Prototype | "A prototype is an artefact that approximates a feature (or multiple features) of a product, service or system" (Otto and Wood, 2003) |
| Feature | A feature describes the products distinguishing characteristics being central to 'what it does' |
| Prototyping strategy | "the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)" (Christie et al., 2012) |

| | |
|---|---|
| Designer | Similar to e.g., Pahl and Beitz, the term ‘designer’ is used synonymously to mean design and development engineers (Pahl et al., 2007). |
| Novice designer | A designer with less than five years of professional working experience in product development (Ahmed and Wallace, 2004). |
| Prototype Fidelity | Prototype fidelity describes what properties, characteristics or behavior the prototype has in common with a product. |
| Prototype Resolution | Prototype resolution describes the refinement of a prototype in relation to the principles applied for its fabrication. |
| Properties | Properties are a behavioral class of devices’ and activities’ attributes, by which they show their appearance in the widest sense and create their relation to the surroundings (Andreasen et al., 2015). |
| Characteristics | Characteristics are a class of structural attributes of products and activities determined by the synthesis of the design (Andreasen et al., 2015). |
| Behavior | Behavior is the system’s response to a stimulus depending on stimuli, structure, and state (Andreasen et al., 2015). |
| Design methodology | An overall framework for doing design (Blessing and Chakrabarti, 2009). |
| Design method | Sequences of activities to be followed to improve particular stages of the design process (Blessing and Chakrabarti, 2009). |
| Design principle | Principles and heuristics that are useful to follow in attaining some design objectives (Blessing and Chakrabarti, 2009). |
| Design tool | Hardware and software for supporting design, based on some design methodology, method or set of guidelines (Blessing and Chakrabarti, 2009). |
| Prototyping framework | A prototyping framework is an overall process model to support the prototyping activity. |
| Best practice | Best practice is an approach or technique generally accepted as superior to alternatives because it is more likely to produce results that are superior to those achieved by other means. |
| “Prototyping mindset” | “Prototyping mindset” A tern derived from “method mindset” proposed by Andreasen, (Andreasen, 2011). Such concern both knowledge about understanding the prerequisites for using a method (know-what), and the skills and ability needed to use it effectively (know-how) (Person et al., 2012). |
| Crowdfunded product development | A product development project taking place in the context of a reward-based crowdfunding campaign (appended Paper B). |
| Digital fabrication | Digital fabrication is a type of manufacturing process in which the machine used is controlled by a computer. Examples include 3d printing/additive manufacturing, laser cutters and other CNC machines. |
| Makerspace | A Makerspace (also referred to as hackerspace) is a community-operated, often not-for-profit work space, where people with common interests, often in computers, machining, technology, science, digital art or electronic art, can meet, socialize and collaborate (Cavalcanti, 2013). Universities and other institutions have adopted the term and created similar, but institutionalized spaces (Jensen et al., 2016). |
| FabLab | A FabLab (fabrication laboratory) is a small-scale workshop offering (personal) digital fabrication. The concept emerged from MIT Center for Bits and Atoms at the Media Lab and has become a global grassroots organized movement (Troxler and Wolf, 2010) |

## 1.5 Thesis structure

This thesis is written as a so-called 'paper-based' thesis. The objective is, as opposed to the conventional monograph, to provide a summary of results and contributions of this research project. As it was introduced in Figure 3 six research papers (paper A-F) and one draft outlining intermediate results (IR) are appended to the thesis and provide supporting detailed information.

Furthermore, four papers have been published or submitted for peer review and function as supplementary materiel. Our intention is for the reader to be able to follow the line of argument throughout the thesis without referring to the supplementary work.

This thesis is structured in eight chapters that can be segmented into three overall parts as outlined in Figure 4. The first parts concern setting the stage and research foundation for this project. The second part summarizes our results and conclusions. With reference to the appended papers we aim at answering our research questions. The structure of chapter four, 'Results', follows the list of appended papers outlined in the prelude.
The third and last part contains references and the six papers appended for this thesis.

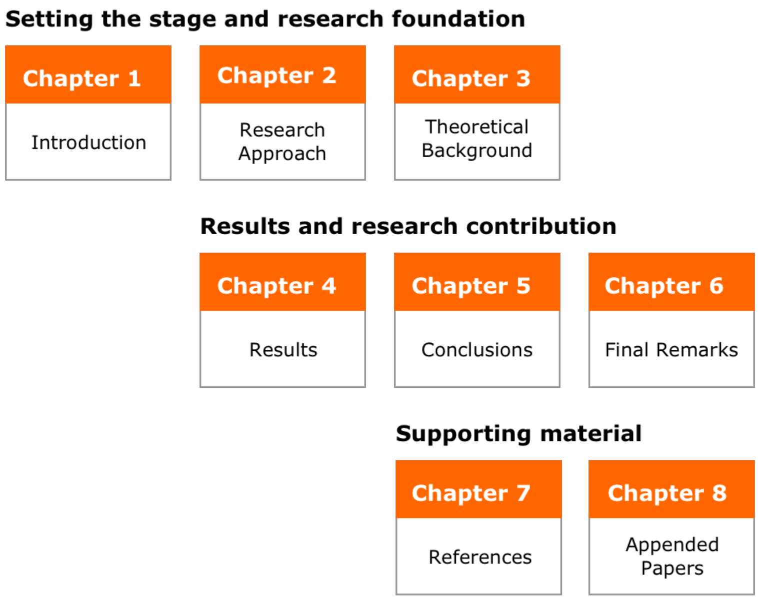



*Figure 4: Overall thesis structure*

# 2 Research Approach

*This chapter introduces the scientific approach to the project. It entails an introduction to the overall methodology applied and the methods and activities, as well as an introduction to the metrics applied to verify and validate the project results. The chapter includes graphical illustrations aiming to provide the reader with an overview of the project and its line of argument.*

---

This research project was conducted in the context of engineering design. The profession of design emerged in the last century (Cross, 2007). *Design* is about studying the creation of artifacts and their embedding in our life and society. Strictly speaking, good design improves our lives and societies, and bad design ruins our lives (Papalambros, 2015).

As Herbert Simon outlined in *The Sciences of the Artificial*, professions like engineering are "concerned not with the necessary but with the contingent – not with how things are, but with how they might be" – in short, with design (Simon, 1996).

A central aspect in design research is hereby to understand how designers both work and think and also how design could be (Cross, 2001). Another part of design research consists of proposing methodologies, principles and tools that can support designing and increase the likelihood that the outcomes of development activities are successful (Blessing et al., 1998).

## 2.1 Research Area and Focus

In the engineering design community, there is a general agreement that research on the topic of design is multidisciplinary and multifaceted. In *Engineering Design*, Pahl and Beitz illustrate this concept by placing engineering design as a topic located in the center of a crossroad of disciplines, as illustrated in Figure 5 below.

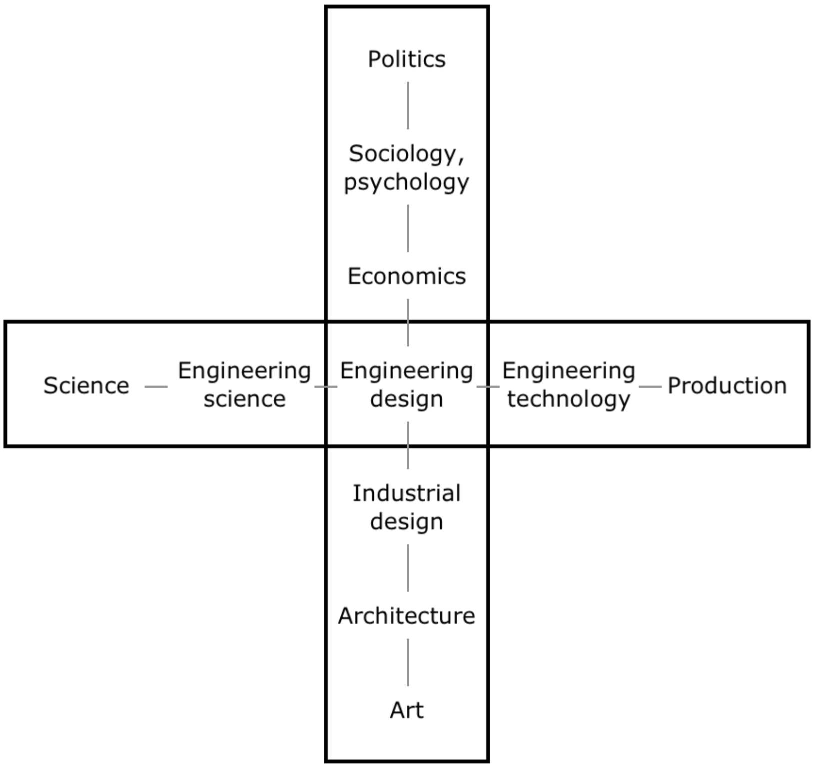



*Figure 5: Engineering design is at a crossroad of disciplines (redrawn from (Pahl et al., 2007))*

Despite this interconnected multidisciplinary and multifaceted nature, design research has two dominating characteristics: it is driven by the twin goals of i) understanding the process of designing and ii) improving it (Eckert et al., 2003).

The main focuses of this project are on understanding the product development and prototyping activates in hardware start-ups, and on studying how these designers can be supported in their development process through design-rooted methods.

### 2.1.1 Focus areas

To outline the research areas in focus and the project objectives, an Areas of Relevance and Contribution diagram (ARC diagram) (Blessing and Chakrabarti, 2009) was established as illustrated in Figure 6.

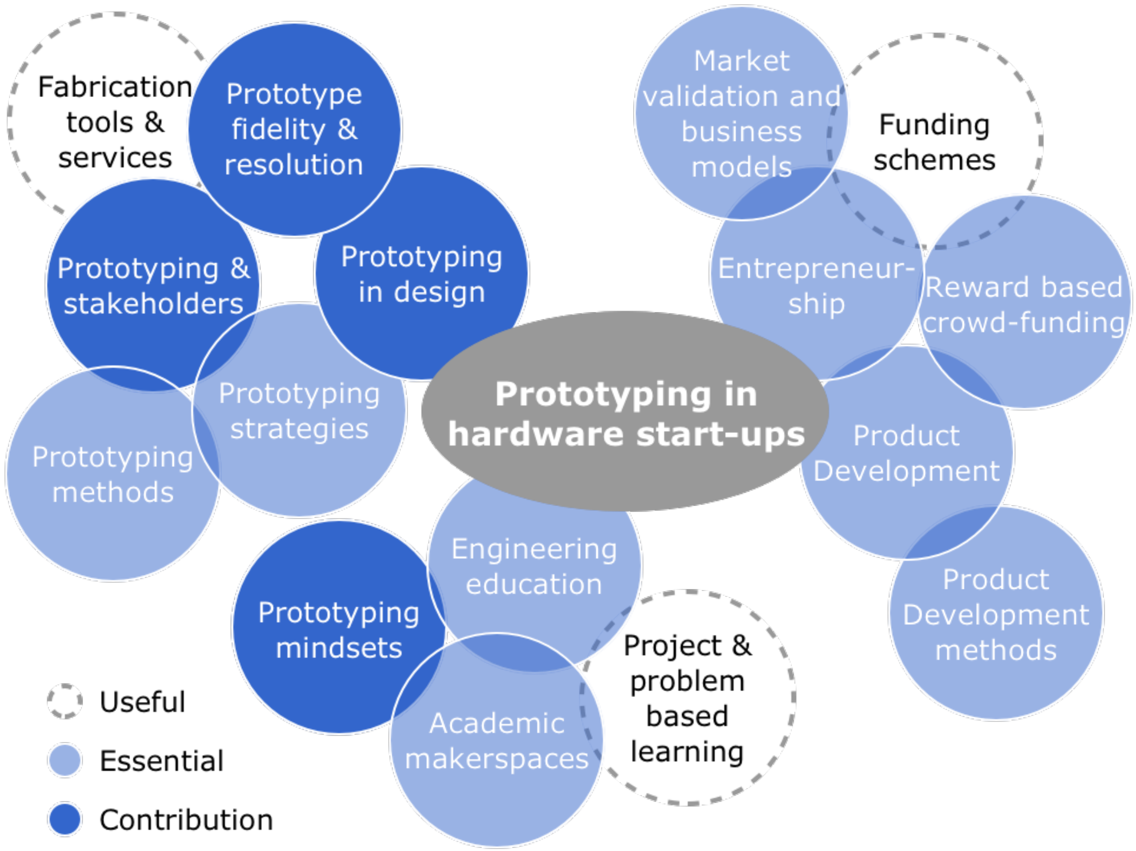



*Figure 6: ARC diagram illustrating the project scope.*

The ARC diagram was established by following the guidelines provided by Blessing and Chakrabarti (2009) and illustrates the main research subject: prototyping in hardware start-ups. In our research context, this focus relates to and draws on three overall research topics. We illustrate those topics as three clusters of the arc diagram. The top left cluster represents the topic of prototyping in design. The top right cluster represents the topic of entrepreneurship, and the bottom left shows engineering education.

The three legends of the arc illustrate how different niche topics within each cluster have been categorized as useful for the research, essential for the research and contributing to the particular topic.

### 2.1.2 Research scope

Research in the topic of design can be conducted at different levels of 'abstraction'. Different categorizations of such have been proposed. One categorization method was suggested by Horváth, who introduced three methodological approaches to design research and described how these approaches function as links, establishing a coherence between basic scientific research and the practice of industrial product engineering (Horváth, 2007). The three approaches cover 'research in design context,' 'design inclusive research,' and 'practice-based design research.' The first domain deals with fundamental aspects of designing, and the latter is conducted close to industry. Their interconnection is illustrated in Figure 7 below.

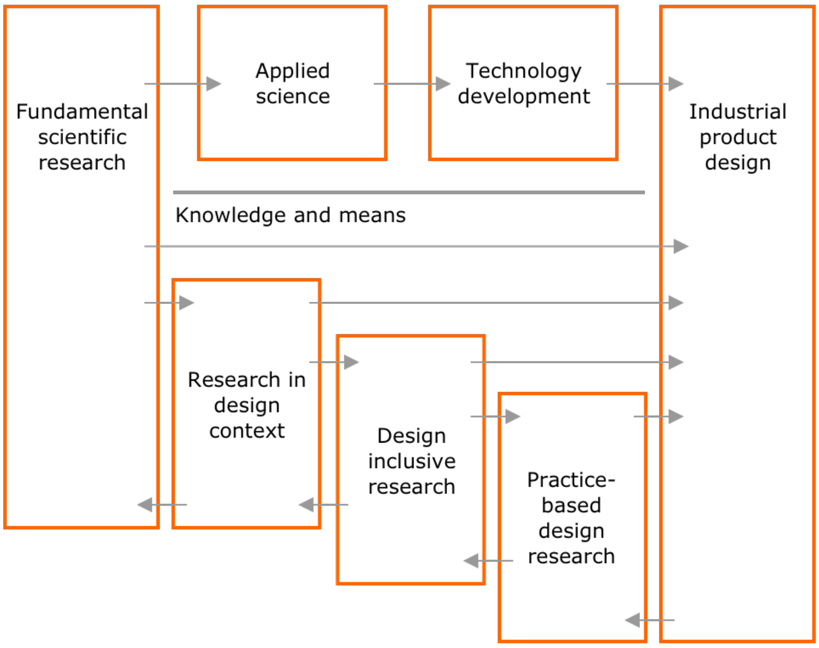



*Figure 7: Illustration of design research and three framing methodologies in context and as connectors of fundamental scientific research and industrial product design (after Horváth,2007).*

The work carried out in this project draws mainly on elements from 'practice-based design research' through a high level of contextualization and integration with concrete design practice. We strive to use a sound theoretical foundation and a robust methodological approach throughout the project, but also to adopt the mindset of the practitioner by observations of design practice, practical design activities and interventions. Hereby such activities should favor the ability to "answer questions that emerge from practice in ways that inform practice" (Horváth, 2007).

## 2.2 Research methodology

Adapting a research methodology can provide support in establishing a strategy of reasoning and indicate possible research designs, essentially guiding the research actions to be done. For this project, the Design Research Methodology (DRM) by Blessing and

Chakrabarti (Blessing and Chakrabarti, 2009) was adopted. DRM is widely recognized in the design community and provides a well-suited framework for projects focused on the development of support tools for designers. Further, the project draws from the modelling of “the Problem-Based and Theory-Based” approach (PbTb) which has been introduced by K. Jørgensen (Jørgensen, 1992)

### 2.2.1 Problem-Based and Theory-Based Approach

The PbTb approach outlines two fundamental approaches for how research can be conducted. As presented in Figure 8 below, the two approaches are rooted in, respectively, a problem or industry-based approach (in this case hardware start-ups), and alternatively in a theory or academic-based approach. In the case of problem-based studies, the point of departure is the observation of a problem or issue, which is analyzed to discover patterns, collect empirical evidence and establish causalities, eventually leading to a diagnosis. From here, solutions can be generated through methods such as synthesis, with the eventual result of new scientific knowledge that can be transferred into practical results.

In the other case, a theory-based approach has theory as its point of departure. Through synthesis of theories, patterns can be identified and models can be established. To understand the validity of models, they must be validated. Novel scientific contributions here lie within models that have a statement strength that can be of value to others.

Despite their fundamental difference, quality research is being conducted through both approaches. In practice many researchers draw from both approaches, and for this project both approaches have been applied throughout. Further clarifications on the particular research activities are provided in section 2.4.

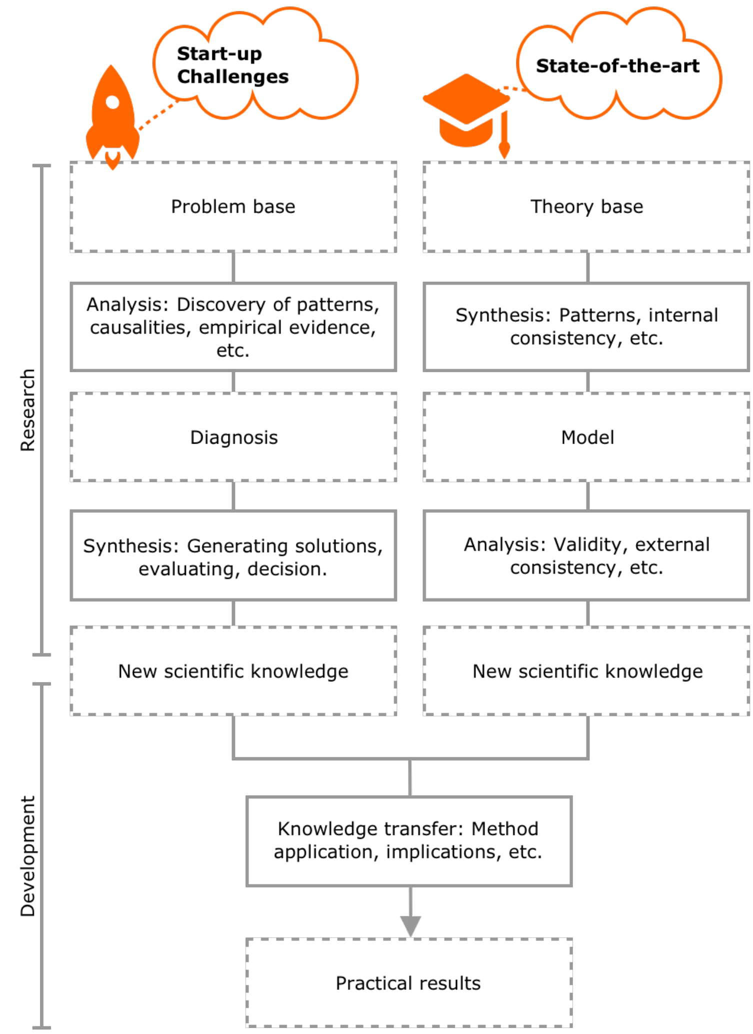



*Figure 8: Design Research Model: Problem-based, Theory-based research approach. Redrawn and freely translated from Danish: (Jørgensen, 1992)*

### 2.2.2 Design Research Methodology (DRM)

As addressed in Section 2.2.1 this project includes characteristics of both 'design-inclusive research' and 'practice-based design research.' These approaches can both be categorized as applied science, and to structure design research with such characteristics, the DRM has been proposed by Blessing and Chakrabarti (2009). The DRM's objective is to provide a consistent and coherent stage-based methodology for the formulation, execution and evaluation of design research projects. The four stages of the generic DRM framework can be seen in Figure 9, which also outlines the basic means and the expected main outcomes.

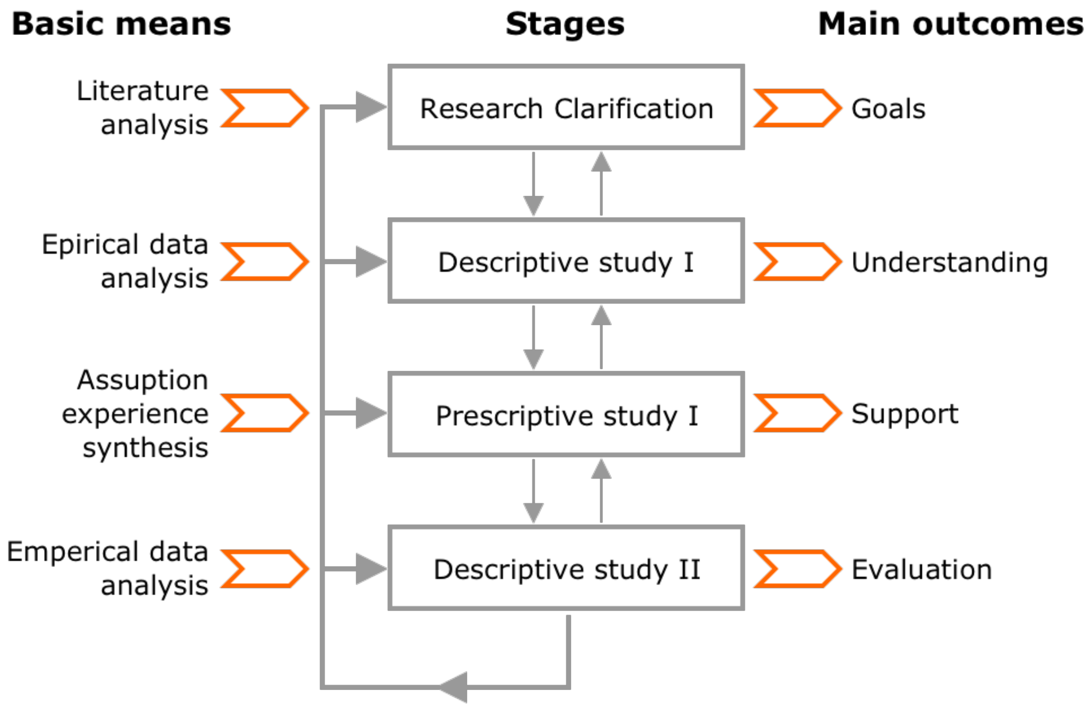



*Figure 9: Overall outline of DRM framework, redrawn from Blessing and Chakrabarti (2009)*

An introduction to each stage of the DRM model is outlined in the following paragraphs.

**Stage I: Research Clarification:**
The starting point of the DRM is the Research Clarification. This step's objective is to develop an understanding of the research topic and overall scope of the project to be carried out. This understanding includes developing beliefs concerning the current and desired situation. More concretely, this step includes identifying goals and the main research problems and questions. Hereby the outcome of the Research Clarification stage is an overall research plan and the formulation of a preliminary understanding that determines the focus on the descriptive study DSI (Blessing and Chakrabarti, 2009).

**Stage II: Descriptive Study I:**
With the offset in the Research Clarification, the Descriptive Study I is concerned with obtaining a detailed understanding of the existing situation and its influencing factors. Important aspects here are to identify the most suitable factors to address in future prescriptive stages to improve the existing situation. This step is further relevant for initiating the development of a reference for evaluation of the developed support, which takes place in the Descriptive Study II. Hereby the Descriptive Study I provides an understanding based on theories and models of the current situation (Blessing and Chakrabarti, 2009).

**Stage III: Prescriptive Study I:**
Based on the knowledge and understanding obtained in the prior stages, support is conceptualized by revisiting the factors to be addressed and the success criteria/indicators. The development of the concept for support and the decision on a focus

for implementation are central activities in this stage. This as an outline evolution plan for measuring the impact of the support, its in-built functionality, consistency, etc. The concrete implementation – and hereby proof of concept – are also to be carried out. Hereby the outcome of the Prescriptive Study I is an understanding based on theories and models of the current situation, including implementation of support as well as an outline evaluation plan for how to measure the impact of the support.

**Stage IV: Descriptive Study II:**
The overall aim of the Descriptive Study II is to evaluate the applicability and success of the support. This can include, for example, assessments of its usefulness, identifiable implications and side effects. Hereby an overall evaluation of the application is possible, which can support further theory and/or model validation. Based on the results of this evaluation, further iterations might be necessary to meet the initial goals. Such activities can be rooted in a need for further verification and validation or redesigns of the support based on new insights obtained throughout its implementation and evaluation.

When adopting the DRM framework for this research project it also means that other approaches have been consciously opted out. Overall this includes classical experimental research approaches often applied in the natural sciences, and models from social sciences where theories of reality are created and sometimes evaluated through observations of interventions to improve our reality. In contradiction to these established approaches DRM was established with the primary aim to “help engineering and industrial design research to become more relevant, effective and efficient” (Blessing and Chakrabarti, 2009). The framework further draws on the authors accumulative experiences of supervising PhD projects in design. It can also be argued that the DRM supports “a common terminology, benchmarked research methods, and above all, a common research methodology in design” (Blessing and Chakrabarti, 2009).
The DRM is however not the only research methodology that has been proposed to structure design research. Two methodologies that are close to DRM are respectively the research framework and methodology of Duffy, Andreasen and O’Donnell, and the Soft Systems Methodology of Checkland (Blessing and Chakrabarti, 2009). The first, is though focused at developing computer support, which limits its applicability for this research project. The latter, is focused on action research activities, which makes the approach more suitable for strictly on-site evaluation in less dynamic research activities than the ones conducted in this project.

To provide an overview of how the different DRM stages relate to the research questions as well as the conducted studies we have combined these with the ARC diagram as illustrated in Figure 10.

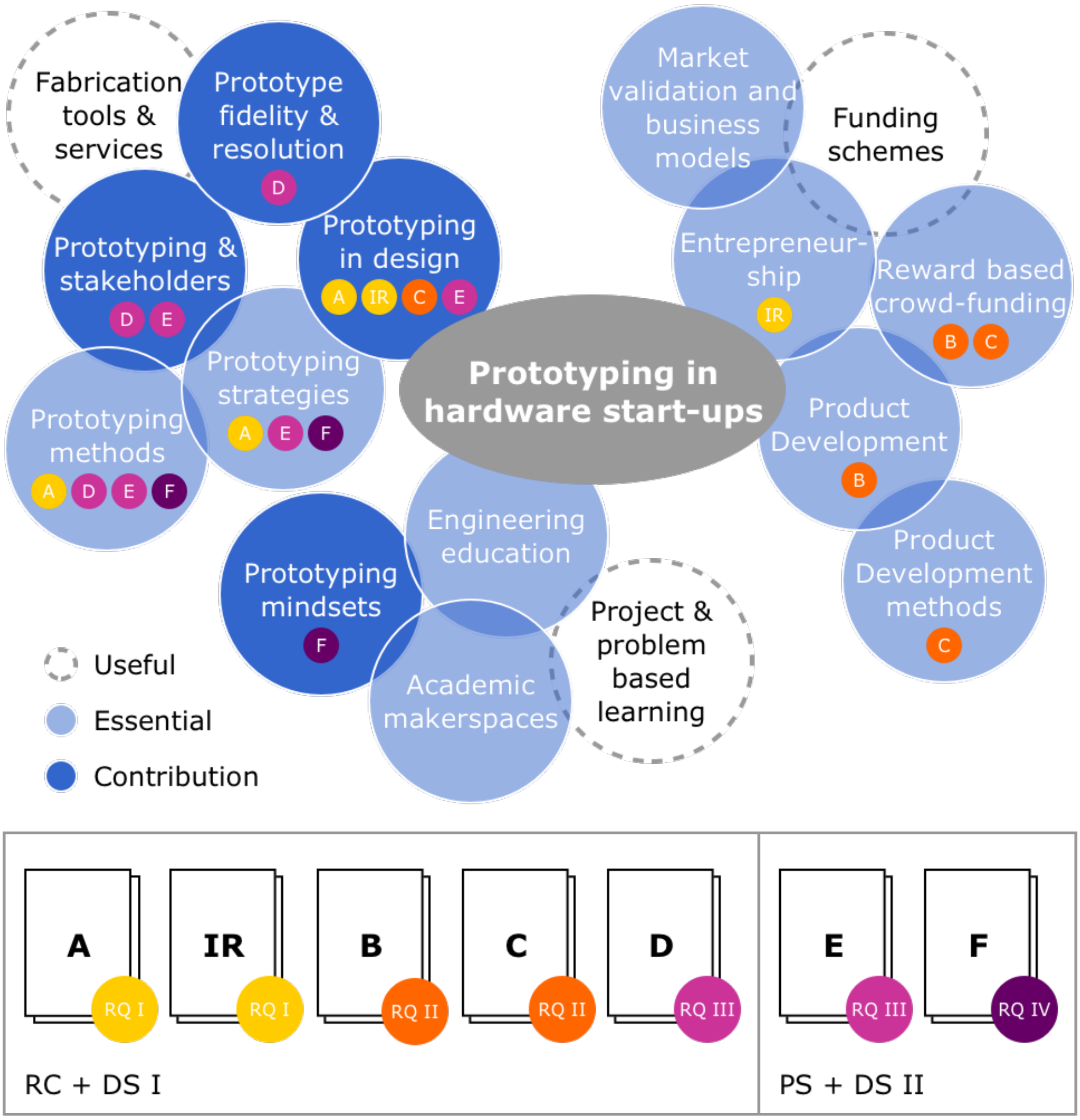



*Figure 10: ARC diagram and relations to research studies and the research questions for the project.*

## 2.3 Research Verification and Validation

Studies in different research fields and traditions draw on varying approaches to verification and validation of results, which is a central element in any research field.

As argued by Pedersen et al., many topics in design research are different from the majority of engineering research, as we deal with open problems in which results can take heuristic traits and representations that cannot be deemed strictly right or wrong (Pedersen et al., 2000).

In the context of DRM, an approach to verification and validation is provided through the concepts of the 'reference model' and 'impact model,' in which measurable criteria are identified in order to monitor success before and after the introduction of design support.

Hereby the impact and quality can be determined (Blessing and Chakrabarti, 2009). Figure 11 Illustrates an example of such a high-level reference model.

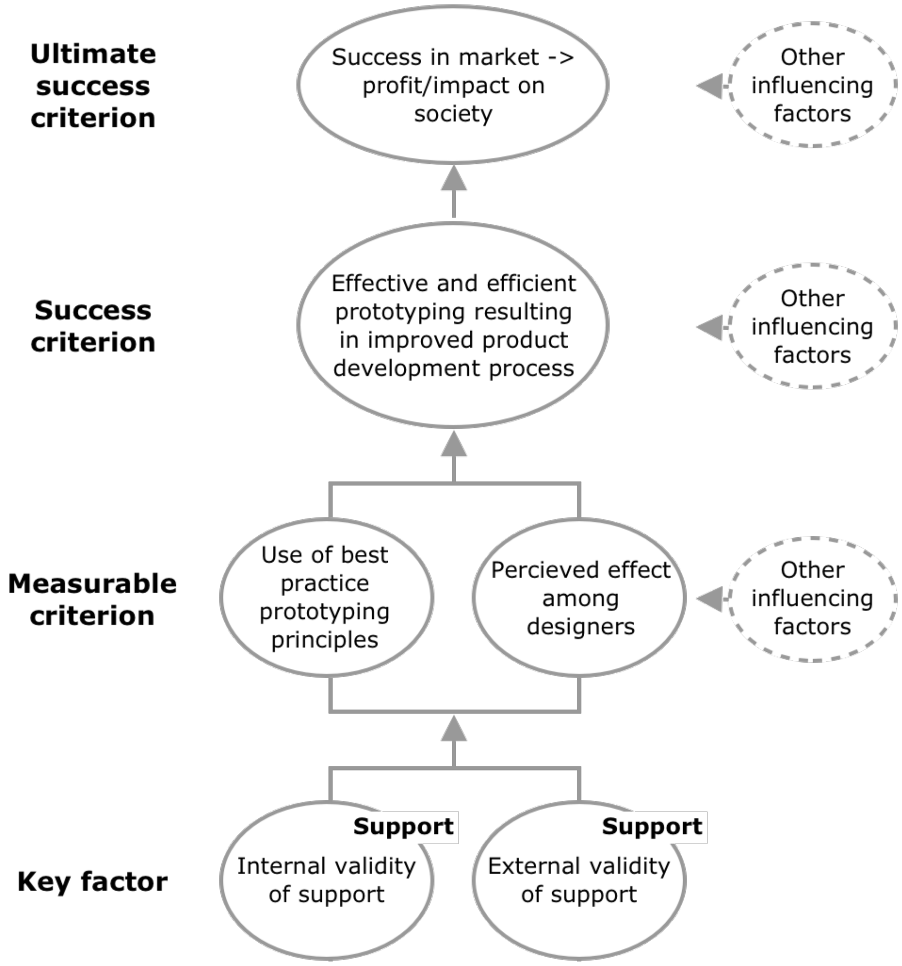



*Figure 11: High level reference model*

From the reference model we can observe that the ultimate success criterion of the hardware start-ups is to succeed in the market, leading to either profit or an impact on society. The success is to be obtained through the success criterion of the product development process. The above criteria, however, are at a level of abstraction that is not suitable for evaluation in this research project. They are affected by many other influencing factors and the timelines might extend to years making such evaluation unfeasible for many research projects. However, a measurable criterion can be identified in the assessment of aspects such as the use of best practice prototyping principles (Deininger et al., 2017a) in the design process or how the designers perceive that the tool supports their design efforts. These tools can serve to validate internal and external validity of support, respectively.

An alternative to the reference model is proposed by Pedersen et al. who argue that it is meaningful for much design research to be validated in the relativistic perspective and that design methods should be validated according to their usefulness with respect to a purpose. Here, usefulness is associated with the method's ability to support the delivery of both effective and efficient design solutions. This concept is further unfolded in their validation square, which is a systematic validation approach.

The general idea of the validation square is to provide an approach to the evaluation of internal consistency and external relevance. This approach comes from both a theoretical and an empirical point of view. The validation square is presented in Figure 12 below.

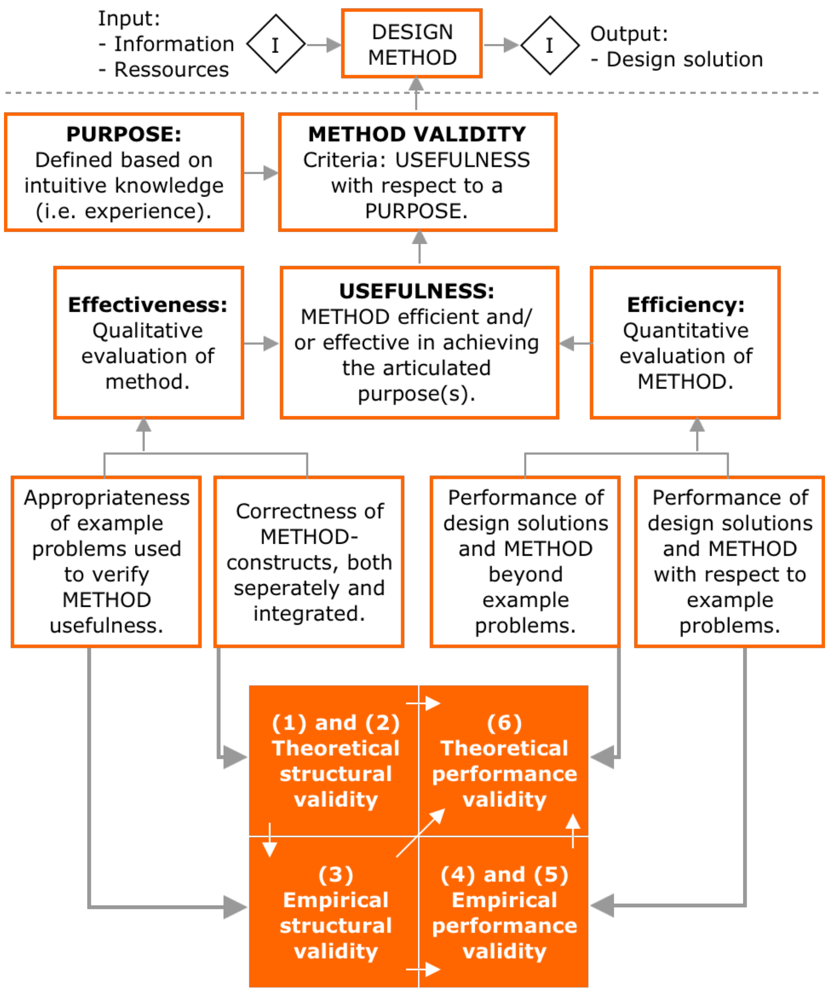


*Figure 12: The validation square, redrawn from Pedersen et al. (2000)*

Besides their connection to the left and the right side of the validation square, respectively, the concepts of effectiveness and efficiency are further elaborated in six aspects as introduced by Pedersen et al. (2000).

Effectiveness embodies:

i) "Accepting the individual constructs constituting the method;
ii) Accepting the internal consistency of the way the constructs are put together in the method; and
iii) Accepting the appropriateness of the example problems that will be used to verify the performance of the method."

Efficiency embodies:

iv) "Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s);
v) Accepting that the achieved usefulness is linked to applying the method; and
vi) Accepting that the usefulness of the method is beyond the case studies."

We will refer back to these two approaches for validation when evaluating our work in Chapter 5, 'Conclusions.'

## 2.4 Research Activities and Research Line of Argument

The methodology introduced in the previous sections has helped establish the foundational structure of this project. Although general methodologies can support overall strategy and structure, they are not the right place to look when it comes to identifying matches among research questions, particular research tasks and research methods.

### 2.4.1 Overview of DRM Stages

To structure how information from concrete activities was to be identified, collected and analyzed in a range of studies, Figure 13 was established. The objective is to establish coherence among the different research questions and research activities and research methods.

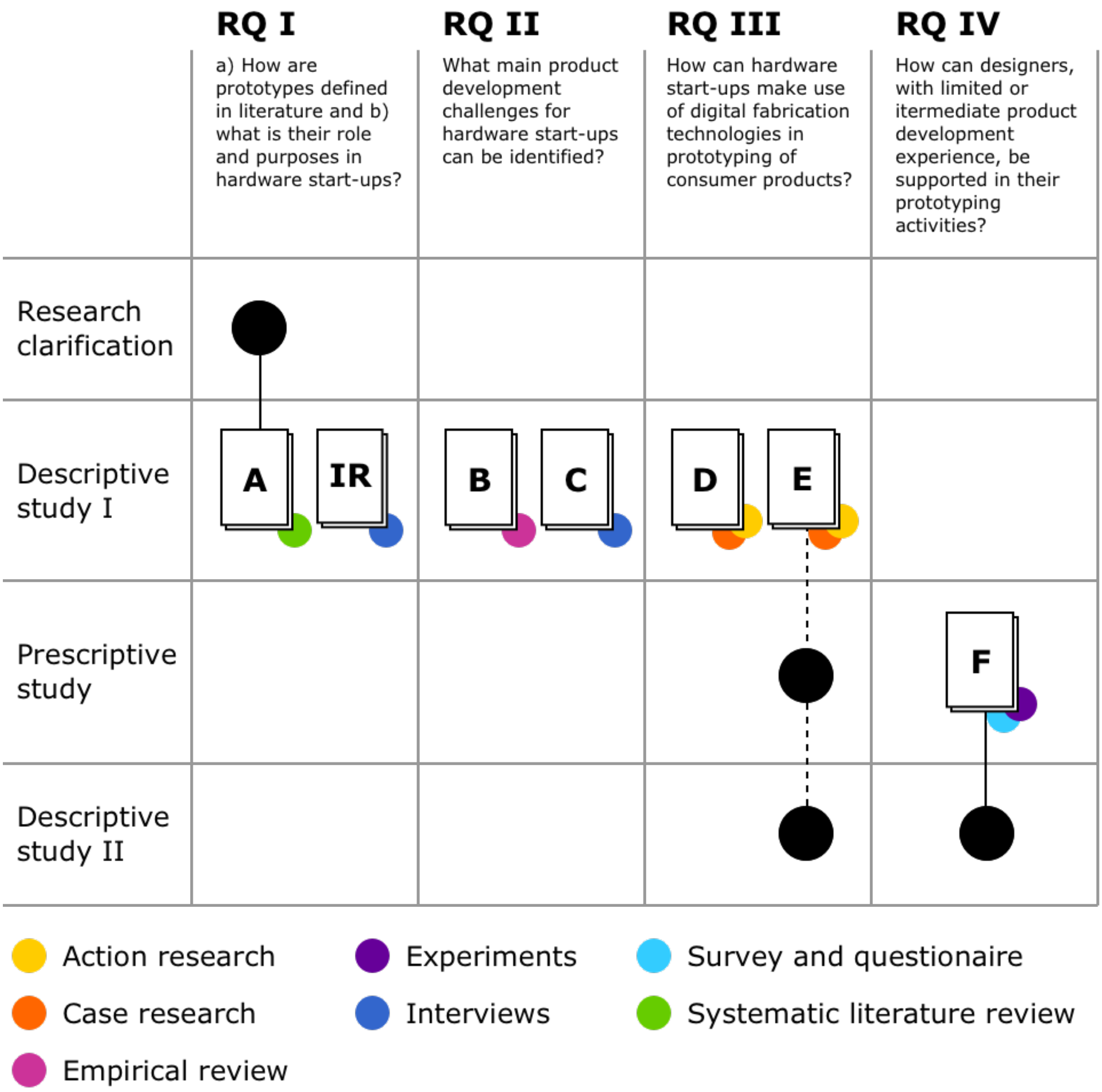


*Figure 13: Overview of DRM stages, research questions and the studies conducted including their respective research methods.*

### 2.4.2 Research methods

"Studies of multi-dimensional problems such as design activity require multi-level, multi-method approaches" (Pessant and McMahon, 1979). In this light an overview of research methods that have been practiced for this project is outlined below, along with short reflections on the concrete choice of methods:

**Action research**

Characteristically, the researcher engages in action research by taking part in the situations. General objectives are to generate practice-based knowledge and extract elements thereof for the establishment of theories and results. AR can serve as a strong tool to identify new research trends, nuances and enable reflections (Checkland and Holwell, 2007), but is also a discipline which has been subject to criticism. It is argued that AR overemphasizes practical problem-solving (Checkland and Holwell, 2007). This criticism can however be at least partially accommodated for when adopting a PbTb approach, as introduced in Section 2.2.1. For this project AR has served the dual purpose of expanding our accumulative understanding of product development (as elaborated in section 2.5.1) and also served as a concrete research method deployed in paper D and paper E, as illustrated in Figure 13. Here we directly supported the involved start-up in research design and data analysis. This however without engaging in any decision making or other interventions to the ongoing development project

**Case research**

Case research is a central element in design research because it provides the researchers with opportunities to investigate 'real world problems' and phenomena empirically. Hereby different research questions can be studied under contextual conditions (Yin, 2009). Case research can involve both qualitative and quantitative research methods. For this project case research was applied for paper D and paper E, where two start-up companies were observed throughout systematic prototyping activities.

**Experiments**

The concept of experiments exists in a range of different formats. For this project we conducted a controlled experiment in Paper F. We studied the design efforts of designers working on a specific design brief. By comparing the outcomes of two samples of designers, one who utilized a support framework and a control group who did not, we were able to evaluate different aspects of our support and also collect empirical material for one of our research questions. The experiment took place in an educational context, which introduces limitations compared to a design activity in industry. On the other hand, the experiment allows for a controlled environment increasing control over the design activities being studied.

**Interviews**

Throughout this project a range of interviews were conducted. We generally used a semi-structured approach (Eisenhardt, 1989). We hereby used a checklist of topics to steer the discussion and often included a range of supporting materials for the interviews to encourage the dialogue. This approach also allowed for direct coding of a range of results from the interviews. Interviews was conducted for the draft IR and paper C and helped us to obtain a detailed understanding of product development and prototyping activities reported in the contexts represented by the interviewees. While interviews have limitations, e.g. from bias of the results, they also allow for collecting a larger sample of cases than what is generally possible from more time-consuming approaches, such as case research and action research.

**Surveys and questionnaires**

Surveys and questionnaires can serve as a useful research tool to capture the thoughts, beliefs, reasons and opinions of relevant stakeholders (Blessing and Chakrabarti, 2009). These data can be relevant for studies of descriptive character as well as a relevant tool to collect feedback on prescriptive interventions in design. While surveys can function as effective tools, it can also be a challenge to design their layout in such a way that biases are minimized and questions are interpreted as intended by the sender. For this project we used surveys and questionnaires for paper F, which allowed us to effectively collect multiple sources of data on our experiment and hereby capture different viewpoints and increase validity of the study.

**Systematic literature review**
Systematic literature reviews are characterized by using a systematic method to collect the literature used for analysis. This method is done according to criteria that determine what literature to include in the study and by providing a summary of study characteristics. The results of the review can include different types of meta-analysis, and the ambition of the review is to provide an exhaustive summary of current literature on a research topic or particular research question (Piper, 2013). A systematic literature review was conducted for paper A, with the objective to obtain an overview of prototyping as a research topic in product development and engineering design. The review was conducted early in the research project, which is encouraged as a central part of the research clarification in the DRM framework (Blessing and Chakrabarti, 2009).

## 2.5 Other research activities

In addition to activities focused on research studies, a range of related activities have been part of this project. In the sections below, I outline an overview of selected activities that have supported my understanding of prototyping as a research topic and activities regarding dissemination of knowledge obtained throughout the project. Further, I provide an overview of academic courses that have been completed as part of the project.

### 2.5.1 Action Research at DTU Skylab

According to Blessing et al., a common starting point for the development of design support is reasoning based on experience and logical argumentation. To follow the actual design processes and behavior of practitioners is important not only for the development of the support, but also for their dissemination and acceptance in industry (Blessing et al., 1998).

Throughout this project, I have held a position as team member at DTU Skylab's 'start-up coaching and prototyping' group. Here I have participated in team meetings, implemented a user-monitoring tool, taken part in a seed stage accelerator program, held meetings with teams of entrepreneurs to support them in prototyping practices, hosted extracurricular crash courses on digital fabrication technologies, and, during busy periods, supported the workshop staff in prototype fabrication. Although these activities have not directly been translated into results documented in academic papers, they have all helped to support my understanding of product development in practice as well as the dynamics of an academic makerspace.

### 2.5.2 Knowledge Sharing and Dissemination of Knowledge

The results of individual studies and work-in-progress points of view have been shared and discussed with peers throughout this project. These discussions have taken place in different research communities and industry contexts and with students, as well as the general public. Altogether such activities have helped to improve and scope the research activities of the project. Table 2 and Table 3 below outline a selection of international and national activities, respectively.

*Table 2: Overview of selected international dissemination activities carried out as part of the PhD project. Conference presentations are not included.*

| **International Activities** | **Location** | **Year** |
|---|---|---|
| Participation in EuroTech Alliance Better Light workshop on entrepreneurship | TU Eindhoven, Eindhoven, The Netherlands | 2016 |
| Participation in Nordic Five Tech Entrepreneurship workshop | KTH Royal Institute of Technology, Stockholm, Sweden | 2016 |
| Research visit at Institute for Product Development and Lightweight Design | TUM & Unternehmer TUM, Munich, Germany | 2017 |
| Presentation on research findings in crowdfunding for Kickstarter.com technology leads | DTU Mechanical Engineering, Kgs. Lyngby, Denmark | 2017 |
| Crowdfunding: What happens after funding? Moderator & organizer of panel discussion in collaboration with Kickstarter.com | DTU Skylab, Kgs. Lyngby | 2017 |
| Public sector consultancy, contributions to report on 'Best Practice in University Makerspaces' for Innovation Centre Denmark, Silicon Valley | Kgs. Lyngby, Denmark | 2017 |
| Presentation on prototyping in hardware start-ups | Hong Kong University, Hong Kong, China | 2017 |
| Presentation on prototyping in hardware start-ups | KHUST, Hong Kong University, Hong Kong, China | 2017 |
| Presentation on prototyping in hardware start-ups | HAX Accelerator, Shenzhen, China | 2017 |
| 2-days' workshop on EU Horizon 2020 project at Institute for Product Development and Lightweight Design | TUM, Munich, Germany | 2018 |
| 1-day research visit at Institute for Product Development and Lightweight Design | TUM & UnternehmerTUM, Munich, Germany | 2018 |

*Table 3: Overview of selected national dissemination activities carried out as part of the PhD project.*

| **National Activities** | **Location** | **Year** |
|---|---|---|
| Talk on the maker movement in Denmark | FabLab Nordvest, Copenhagen | 2015 |
| Moderator in panel discussion: "Prototyping: Why and How?" | DTU Skylab, Kgs. Lyngby | 2015 |
| Talk on prototyping in European Venture Program Summer batch 2015 | DTU Skylab, Kgs. Lyngby | 2015 |
| Presentation on academic makerspaces for 'Medico Innovation' networking group | DTU Skylab, Kgs. Lyngby | 2016 |
| Guest Lecture: "Commercialization of high tech concepts, entrepreneurship and science in action." | Copenhagen Business School, CBS, Frederiksberg | 2016 |

| | | |
|---|---|---|
| Script and speak on 12 'Design for 3D printing' eLearning videos for lab course | DTU Mechanical Engineering | 2016 |
| Presentation on learnings of 2 years of 'E-learning in Lab-Based Teaching' at DTU | DTU Biannual seminar on teaching and learning, Kgs. Lyngby | 2017 |
| Makerspaces in Engineering Education presentation for delegation of 9 Erasmus Plus universities from Eastern Europe | DTU Skylab, Kgs. Lyngby | 2017 |
| 'Hands on' prototyping workshop for Copenhagen Health Incubator | DTU Skylab, Kgs. Lyngby | 2017 |
| Teaching Assistant in Course 41030, 'Design of Mechatronics' | DTU Skylab & DTU Mechanical Engineering, Kgs. Lyngby | 2015 - 2018 |

### 2.5.3 Academic PhD courses

Table 4 provides an overview of completed academic courses at the PhD level in partial requirement for the fulfillment of the PhD project.

*Table 4 Academic PhD level courses completed as part of the project.*

| **Course Title** | **Institution** | **ETCS** | **Year** |
|---|---|---|---|
| How to Write a Scientific Paper | DTU Civil Engineering | 5 | 2015 |
| Patent Course | DTU Management Engineering | 3 | 2016 |
| Introduction to Quantitative Research Methodology | Aarhus University, Department of psychology and behavioral sciences | 5 | 2015 |
| "Summer School of Engineering Design Research" | DTU Mechanical Engineering & UniZG, Faculty of Mechanical Engineering and Naval Architecture | 5 | 2016 |
| "Introduction to Statistics and R Programming for PhD Students" | DTU Compute | 5 | 2017 |
| Research Design for the Development and Evaluation of a Prototyping Tool for Product Development | DTU Mechanical Engineering | 5 | 2018 |
| | | Total: 28 | |

# 3 Theoretical Background

*This chapter introduces the underlying theoretical background for this project. The overall purpose is to outline relevant theories and methods, as well introduce the state of the art in design research on prototyping. This chapter's intention is to provide enough information for the reader to position this project according to the existing knowledge base, but for elaborate detailed information the reader is referred to the provided references.*

## 3.1 Scoping of the theoretical basis

Product development is often described though process models. A range of acknowledged models have been proposed over the years, and examples are those suggested by Pahl and Beitz (Pahl et al., 2007) and Nigel Cross (Cross, 2008), as well as the V-model for mechatronic products (VDI 2206, 2004) . For several years such process models have been considered industry standards (Ovesen, 2012). However, process models require up-front planning and are often inappropriate when applied to development activities with characteristics of uncertainty (Ovesen, 2012).

Alternative approaches have been suggested for those working in conditions of high uncertainty, such as approaches for working in the 'fuzzy front end of innovation' (Elverum et al., 2014). Also, the notion of design thinking has received wide attention for its ability to tackle challenging problems and provide innovative product solutions (Leifer and Steinert, 2014). Others have suggested transferring the well-known agile principles from the software domain to the development of hardware products. (Punkka, 2012), (Hostettler et al., 2017).

Common to all suggested approaches is that prototyping is considered one of the supporting approaches that can support fruitful development activities. Prototyping is acknowledged as an integrated and interwoven product development activity. In this chapter we will introduce theoretical aspects from the topics of:

- Product development characteristics of hardware start-ups
- How prototypes are understood in engineering design
- Approaches to prototyping and an overview of existing prototyping support tools

## 3.2 Product Development in hardware Start-ups

Product development in start-up companies has some particular characteristics. In the following sections we outline what such characteristics are, but first, we start by defining the term 'hardware start-ups.'

### 3.2.1 What is a hardware start-up?

A range of definitions of the term 'start-up' can be found in the literature. One of these is provided by Blank, who offers the following definition: "A start-up is a temporary organization in search of a scalable, repeatable, profitable business model" (Blank, 2012) It is common practice to differentiate between software and hardware start-ups (Stock and Seliger, 2016). Software start-ups operate in the software domain to deliver a product such as an app or web service. Hardware start-ups are focused on the development of a tangible product, and the product does often (but not always) have mechatronic characteristics and consist of mechanical, electronical and software components.

When characterizing start-up companies, Aulet suggested a distinction between their innovation approach and introduced the two terms ‘small and medium enterprises’ (SME) and ‘innovation driven entrepreneurship’ (IDE) (Aulet, 2013). SME entrepreneurship refers to start-ups that serve local markets with traditional, well-understood business ideas. The concept of IDE entrepreneurship is focused on global opportunities and bringing customers new innovations that have a clear competitive advantage and high growth potential.

For this project we adopt the definition provided by Blank (2012) but limit our work to the hardware domain of consumer products and mainly focus on the IDE entrepreneurship domain.

When using the term ‘hardware,’ we refer to products that are mechatronic or cyber physical products that draw on other fields such as mechanical, electrical or software engineering as well as other disciplines (Schmidt et al., 2018a). When characterizing hardware start-ups, we refrain from using the term tech- or technology-driven start-ups, as the IDE characteristics can exceed technology and also be rooted in processes, business models and more.

### 3.2.2 Product development characteristics of start-ups

A range of characteristics for the development of products in hardware start-ups can be outlined along different dimensions. Table 5 below outlines examples of such characteristics along seven dimensions that all – directly or indirectly – affect the development activities. It should further be noted that the dimensions introduced by Sutton (2000) are reported in the context of software start-up albeit, generally valid for much of the start-up population.

*Table 5: Development dimensions and particular characteristics of start-up companies.*

| **Dimension** | **Characteristic** |
|---|---|
| Resources | Start-ups are typically particularly limited in resources (Sutton, 2000) |
| Team operating history | Start-up companies are typically new and inexperienced compared to more established and mature development organizations. They have little accumulated experience or history (Sutton, 2000). |
| Development processes | Organizational dynamism practically precludes repeatability. New processes occur under new circumstances, and the processes are subject to change as those circumstances change (Sutton, 2000). |
| Use of methodology | Systematic methodologies requires process maturity, which is often not suitable for start-ups (Sutton, 2000) |
| Decision making | Makes use of heuristics and exhibits biases for making decisions as quickly as possible under uncertainty (Zhang and Cueto, 2017). |
| Influencers | Start-ups are particularly sensitive to influences like investors, customers, partners, and competitors that affect decision making (Sutton, 2000) |

| | |
|---|---|
| Uncertainty | Uncertainty and time pressure in start-ups is high. "Don't let the casual dress and playful office environment fool you." New enterprises operate under do-or-die conditions (Iman, 2018). |

In popular terms, product development characteristics like the ones outlined in Table 5 are sometimes referred to as 'VUCA conditions.' VUCA stands for 'volatility, uncertainty, complexity and ambiguity,' terms that are representative of today's competitive consumer markets (Schmidt et al., 2018b).

Although it is generally received knowledge that start-ups work under uncertain conditions and often with limited resources available, we find it worthwhile to underline two of the outlined characteristics;

- Teams are often inexperienced and have little accumulated experience (Sutton, 2000).

As in many other aspects of life, designers rely on their existing knowledge and previous experiences as a part of their design activities. When studying the diversity between experts and novices, it has been found that design methods can elevate the performance of inexperienced designers. This raises the performance of novices to a level at which experts and advanced beginners perform equally well when working on non-routine situations (Daalhuizen and Badke-Schaub, 2011). This observation suggests that support tools for start-ups might be of high value.

- Start-ups often exhibit biases for making decisions under high uncertainty (Zhang and Cueto, 2017)

Studies show that prototypes can support reduction of uncertainty and improve collaboration and group communication as well as problem understanding in design teams (Vetterli et al., 2012). Prototypes are hereby important tools in such situations of uncertainty, but to work with prototypes also requires prototyping specific knowledge, which has been identified as a underdeveloped competence among novice designers (Lauff et al., 2017)

In conclusion, there seems to exist a need to support hardware start-ups in their prototyping activities to improve overall product development.
Paper F further outlines more detailed aspects of lacking competencies for prototyping among novice designers, that can be identified in the existing literature.

## 3.3 Prototyping in design research

This section concerns how prototypes are understood and defined within the design research community.

### 3.3.1 What is a prototype?

The term 'prototype' can have different meanings, purposes and characteristics. In one of our previous studies we presented how at least 19 definitions of the term exist in engineering design and product development literature (appended Paper A). Such fragmented terminology stems from different industries, traditions and research topics.

Within the design community there seem to exist some rather different perceptions of what defines a prototype. We have referred to two of these views respectively as *a validation prototype view* and *a total prototype view* (appended Paper A). Figure 14 below provides an illustration of how these two views are different.

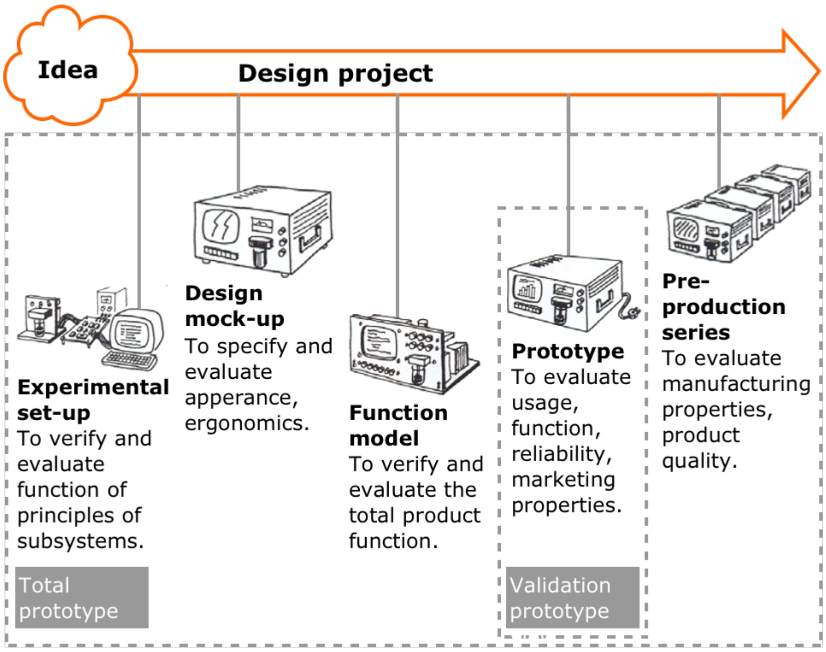



*Figure 14 Two views on what defines a prototype. Figure made with inspiration from Buur (1989)*

The group "validation prototype view" "define a prototype as a mature model of a product before commitment to production is made" (appended Paper A). Such understanding of prototypes is represented by Buur (1989), Kirjavainen et al. (2005), Deon J. de Beer et al. (2004), and others. The second group follows a broader perception of prototypes, and every model representing a product or idea is considered a prototype. One a representative of such understanding is Yang, who specifically states that prototypes can be used at all stages of the design process (2005). This broad view of prototypes seems to have gained the widest recognition in recent years (Camburn, 2015; Jensen, 2017; Menold, 2017), and hereby we adopt this view for this project and use the prototype definition written by Otto and Wood, stating that: "a prototype is an artefact that approximates a feature (or multiple features) of a product, service or system" (2003).

### 3.3.2 Characteristics, applications and purposes of prototypes

As previously mentioned, prototypes can serve various purposes and have characteristics. At an overall level, Lim et al. have underlined the differentiation between "prototypes as design manifestations" and "prototypes as design filters" (Lim et al., 2008). These categories essentially describe how prototypes can serve respectively divergent (ideation, synthesis) and convergent (evaluation, selection) purposes in a product development process.

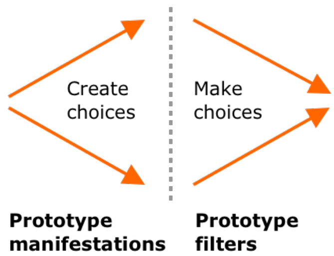


*Figure 15: Illustration of prototypes as manifestations and prototypes as filters. Figure made with inspiration from (Lim et al., 2008)*

Awareness of this overall distinction is relevant as it underlines two rather different thinking approaches and objectives, as illustrated in Figure 15 above.

In the popular product design and development textbook by Ulrich and Eppinger, a two-dimensional plot is used to describe different types of prototypes, as presented in Figure 16 below (Ulrich and Eppinger, 2007). The first dimension focuses on the physical vs. analytical (software/simulation) prototypes, while the second dimension focuses on degree of integration, e.g., the degree to which the prototype embodies all the attributes of the product.

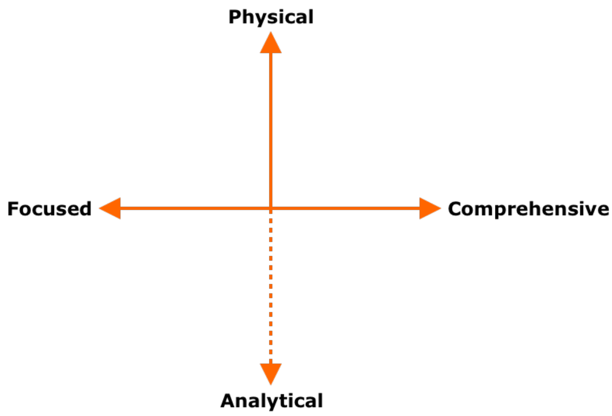


*Figure 16: Two-dimensional plot for classification of prototype types. Redrawn from Ulrich and Eppinger (2007)*

This two-dimensional way to think about prototypes is relevant to highlight, as it conveys the information that prototypes can widely vary in their focus and scope. Note how the "negative" part of the y-axis has been plotted as a dashed line, as software and simulation prototypes are not within the focus of this project.

The authors further outline four purposes of prototypes.

- *Learning:* is used to answer the type of questions "Will it work?" or "How well does it meet customers' needs?"
- *Communication:* Prototyping enriches communication with various stakeholders such as management, vendors, partners, extended team members, customers and investors.
- *Integration*: Prototypes can be used to ensure that components and subsystems of the product work together as expected.

- *Milestones*: Particularly in the later stages of product development, prototypes are used to demonstrate that the product has achieved a desired level of functionality.

Similarly, other popular textbooks on mechanical engineering and product development provide a high-level classification of prototypes based on their purpose or design intent (Otto and Wood, 2003; Ullman, 2010). Examples are "proof of concept prototypes" and "production prototypes," which share the characteristics of being relevant to successive design stages.

Also, recognized practitioners have suggested classifications of prototypes. The US-based pre-seed hardware accelerator BOLT has presented a development model that includes four types of prototypes, as outlined in Figure 17 (Einstein, 2015).

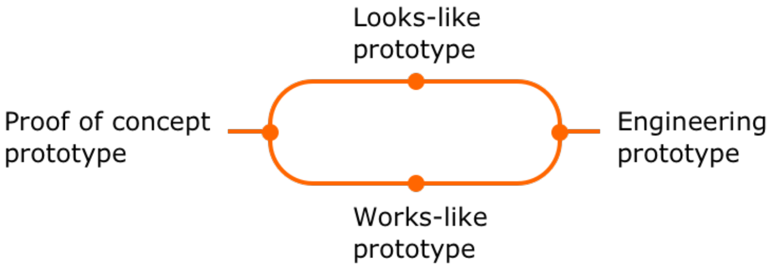



*Figure 17: Simplified illustration of the product development model proposed by BOLT.io including four types of prototypes.*

The classification introduced by BOLT has functionality and characteristics in focus and, to a lesser extent, design stages. Proof-of-concept-prototypes intend to validate the functionality of central design aspects; works-like prototypes represent aspects of the product's functionality; looks-like prototypes represent the design and aesthetics of the product; and lastly, engineering prototypes represent a merger of the product design and the product functionality, allowing for various manufacturing-related evaluations.

### 3.3.3 Prototype taxonomies

Given the broad range of applications, purposes and embodiments of prototypes, researchers have identified needs for proposing taxonomies of design representations. Through a literature study, Pei et al. established a taxonomy of visual design representations. By evaluating their data body, they suggest four overall groups in the taxonomy consisting of sketches, drawings, models and prototypes (Pei et al., 2011).

This taxonomy can provide an overview of different prototypes and their particular embodiment characteristics. However, it seems limiting not to evaluate the purpose or utilization of the prototypes. As previously outlined in Figure 20, the sense and meaning of prototypes are established through the particular design activity in which they are used.

A different approach for establishing a taxonomy of prototypes, accounting for the prototypes' purpose, has been proposed by Hannah et al. Through a literature study the authors provided a taxonomy of physical prototypes that builds on the fundamental assumption that "the factors taken into account [frontloaded] when fabricating a physical prototype prescribe the characteristics of that prototype" (Hannah et al., 2008). The taxonomy is presented in two overall groups: factors of a physical prototype and characteristics of a physical prototype. The secondary taxa under “Factors of a Physical Prototype” are aspects that need to be taken into account when planning to build a prototype—namely, Communication, Evaluation Purpose, Cost, and Design Stage. The secondary taxa under “Characteristics of a Physical Prototype” are descriptive characteristics of the prototype, namely; Size, Type, Material, and Fabrication. The taxonomy is illustrated in Figure 18.

| **Factors of a Physical Prototype** | | |
|---|---|---|
| Communication | Intent | Declarative (Inform, Record) |
| | | Interrogative (Request, Propose, Test) |
| | | Imperative (Guide, Commit, Decide) |
| | Mode of Communication (Visual, Tactile, Auditory, Mixed) | |
| Evaluation Purpose | Single Design | Form (Is it acceptable, what is good/bad |
| | | Function (Does it function, how well does it perform) |
| | | Fit (will it fit, how well does it fit) |
| | Multiple Designs | Form (which ones are acceptable, which one has better visual, tactile, and/or auditory appeal) |
| | | Function (which ones work, which one performs better) |
| | | Fit (which ones fit, which ones fit better |
| Cost | Time (fabrication, procurement) | |
| | Availability (internal resources, external resources) | |
| Design Stage (Clarification of the task, conceptual, embodiment, detailed, production) | | |
| **Characteristics of a Physical Prototype** | | |
| Size | Number of parts relative to the final sub-system | |
| | Number of disciplines | |
| | Number of constraint questions that can be answered | |
| | Number of criteria questions that can be answered | |
| | Relative scale (dimensioned) to final | |
| Type (Novel, Variant) | | |
| Material | Intrinsic Properties | |
| | Processed Form | |
| Fabrication | Joining methods | |
| | Part production processes | |

*Figure 18 Taxonomy of physical prototypes. Redrawn from Hannah et al. (2008).*

## 3.4 A theory for the prototyping process

Designers make use of prototypes. Some use them all along the development process. Some might only use them for verification, and some only for early conceptualization. Independently of when prototypes are used and how they integrate in an overall development process, we can provide a theoretical understanding of prototyping as an activity.

A central aspect of prototyping is how well a particular prototype articulates something about the future product. Figure 19 illustrates how every prototype is intended to have some “common characteristics” with the future product or object being designed. These “common characteristics” are the properties that can communicate something about the future product and essentially determine what the prototype is able to articulate about the product's properties, behavior or appearance. In other words, the "common characteristics" are what determine the explanatory power of the prototype (Andreasen et al., 2015).

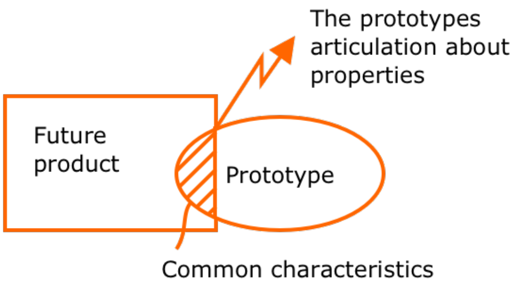



*Figure 19: Illustration of the common characteristics between a prototype and the future product. Drawn with inspiration from Andreasen et al. (2015) where the notion of model is used by the authors rather than prototype .*

A similar line of thought has been introduced by Houde and Hill (1997), who ask the fundamental question "What do prototypes prototype?" and claim that understanding what kind of prototype to build with a limited and clear purpose is a highly complex activity, in which there is not necessarily a coherence between the label of the optimal prototype and the maturity level of the design, which is in contradiction to the specific purpose classification of successive design stages outlined in the popular textbooks on mechanical engineering (Otto and Wood, 2003; Ullman, 2010).

By definition, prototypes are simplified. Andreasen describes how the relationship between the prototyping activity and the future product can be considered to constitute a theory, as illustrated in Figure 20 below (Andreasen et al., 2015).

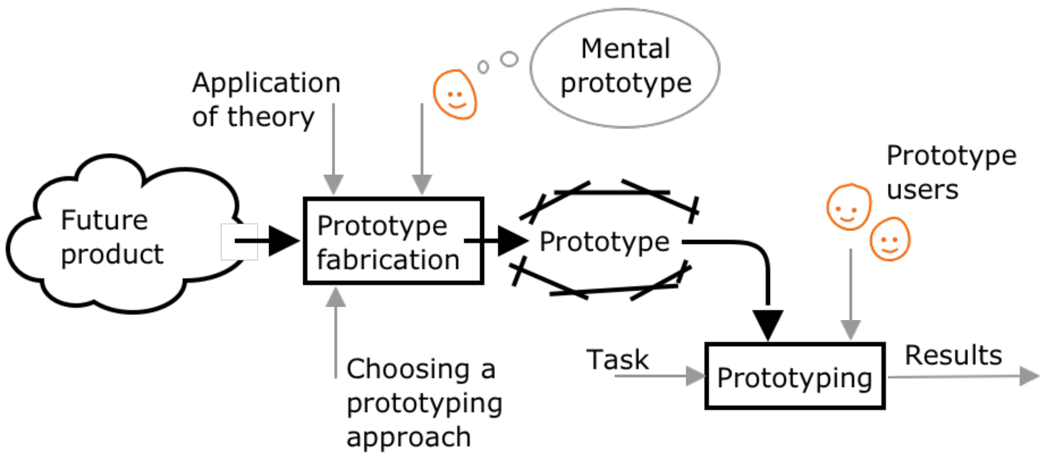



*Figure 20: A theory of the prototyping process. Drawn with inspiration from Maier et al. (2014).*

Figure 20 illustrates the prototyping cycle ranging from design question in the mind of the designer to the resultant answers from conducting a prototyping activity. In the initial stage, the prototype is defined and fabricated. In this process, the assumptions or known theory of the prototype-designer are incorporated in the prototype, along with the designer's mental model thereof. This process is inevitably also affected by the chosen fabrication principle and the chosen resolution or fidelity, among other factors. When the prototype is exposed to a design activity, such as one involving stakeholders and a particular instantiation, the received output or decoded information is also affected by the construct. Eventually the process leads to results which can then be integrated in the further development towards a future product.

A central characteristic for all prototyping activities is that some information is coded when the prototype is created and then again when the information is decoded – through exposing the prototype to a particular activity, as illustrated in Figure 21.

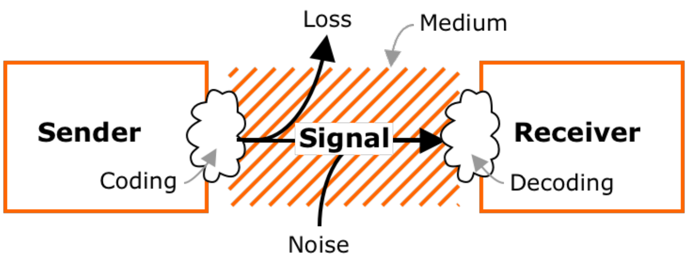



*Figure 21: Prototyping process in which information is coded and decoded. Redrawn from Buur (1990).*

Throughout this process an amount of information will be lost, and noise will be introduced, potentially affecting the decoded result.

## 3.5 Prototyping approaches

A wide range of design heuristics and prototyping best practice principles has been suggested over the years. Also, a few support tools have been proposed. The objective of the following sections is to provide a general overview hereof.

### 3.5.1 Guidelines for prototyping product development

In a recent review, (Camburn et al., 2017) provide a review of "how" and "when to prototype." A result of the review is a table-based overview of literature findings, which can be used to combine prototyping variables and design heuristics. A similar table is illustrated in Table 6 below.

*Table 6: Overview of prototyping variables and related design heuristic. Redrawn from (Camburn et al., 2017)*

| **Variable** | **Design Heuristic** |
|---|---|
| Testing | Construct a clear testing objective |
| Timing | Early prototyping is the most critical |
| Ideation | Prototypes lead to functional ideas |
| Fixation | Fast prototyping reduced fixation |
| Feedback | Feedback may induce corrections but also increase fixation |
| Usability | End-user testing may enhance performance assessment accuracy |
| Fidelity | Higher fidelity representations lead to accurate interpretations of the design |

Without the intention to provide an exhaustive presentation, the paragraphs below provide overall exemplar reflections and references on the introduced variables and heuristics.

Testing: A key objective when prototyping is to acquire sufficient information to move the project forward (Otto and Wood, 2003). According to Camburn et al., the most important design heuristic for prototype testing is hereby to clarify the testing objective (Camburn et al., 2017).

Timing: A central aspect for all development projects is when to engage in prototyping activities. While prototyping is a highly contextual activity, different studies underline the value of early prototyping. Studies of the design of defense systems suggest that early prototyping is a strong tool for mitigation of risk (Rothenberg, 1991) and projects in which early prototyping took place are associated with a higher likelihood of success (Jang and Schunn, 2012). Others also suggest that early prototyping should start with the areas with highest uncertainty (Otto and Wood, 2003).

Ideation: Different tools and methods can be applied to support the ideation process. As the concept was previously introduced in relation to Figure 15, prototypes are not only for design evolution but can also serve to stimulate ideation activities. Different studies support the notion that use of prototypes throughout the ideation phase leads to more functional ideas (Neeley et al., 2013), (V. Viswanathan and Linsey, 2012), (V. K. Viswanathan and Linsey, 2012). A study of industry practitioners has also reported how designers generate new ideas from the fabrication of prototypes in the ideation process (Hess and Summers, 2013).

Fixation: It is a well-known phenomenon that designers can be biased from fixation on a particular design solution. Building prototypes can help designers in reducing design fixation (Viswanathan, 2014), which is found to be particularly true of prototype iterations (Viswanathan and Linsey, 2013), whereas cumbersome prototyping can slow down ideation to a point at which variety will suffer due to the Sunk Cost Effect. This effect pertains to an individual's reluctance to choose a different path of action once significant investments in money, time or effort have taken place (Viswanathan and Linsey, 2013).

Feedback: How to best collect feedback on prototypes from relevant stakeholders, for example, is a central design challenge. Both Deininger et al. and Jensen et al. have shown that prototype fidelity affects the feedback provided by stakeholders (Deininger et al., 2017b),(appended Paper D). Studies have indicated that collecting feedback on a design can increase fixation on a particular design concept (Kershaw et al., 2011), whereas such fixation can be mitigated by including multiple designs in stakeholder interactions (Dow et al., 2009).

Usability: In the ever more competitive global market it is essential to capture the viewpoints of consumers. One approach for doing so is through usability testing with potential customers (Carulli et al., 2013), which can enhance performance assessment accuracy.

Fidelity: What fidelity of prototypes to use for a particular test or exposure of a prototype is a common question faced by designers. The question implies the paradox that resource-efficient prototypes might lack the required level of resolution to collect reliable or appropriate feedback. Building on this paradox, Schmidt et al. have suggested the concept of media richness theory to evaluate the required prototype fidelity in specific situations (Schmidt et al., 2017).

### 3.5.2 Prototype techniques and associated objectives

Another central aspect in prototyping is to combine the desired objectives of prototyping and the applied prototyping techniques. By reviewing the existing literature Camburn et al. suggested combinations in which successful evidence is documented (Camburn et al., 2017). Such situations are illustrated in Table 7 below, in which the checkmark indicates correlating evidence.

*Table 7: Prototyping techniques versus associated objectives. Redrawn from (Camburn et al., 2017).*

| | | Prototyping objectives | | | | | |
|---|---|---|---|---|---|---|---|
| | | Refinement | Exploration | Communication | Active Learning | Reduce Cost | Reduce Time |
| Prototyping Techniques | Iterative Prototyping | √ | | | | | |
| | Parallel Prototyping | | √ | | | | |
| | Requirement Relaxation | | | √ | √ | √ | √ |
| | Subsystem Isolation | | | | | √ | √ |
| | Scaled Prototyping | | | | | √ | √ |
| | Virtual Prototyping | | | √ | | √ | |

The prototyping techniques outlined in Table 7 were identified in the work of Christie et al., who provided heuristics for improved prototyping activities, based on inputs from expert designers (Christie et al., 2012). Here, *iterative prototyping* refers to the activity of sequential testing and refinement of a prototype. *Parallel prototyping* represents the concept that multiple design concepts are being conceptualized and are undergoing concurrent comparisons. *Requirement relaxation* is applied when a prototype is developed to address a subset or reduced version of the defined design requirements. The approach leverages the trade-off between, for example, the development speed and cost versus prototype resolution (Otto and Wood, 2003). *Subsystem isolation* can be identified on the negative x-axis in Figure 17, which allows for focusing on a subsystem of the total design. The purpose of *scaled prototyping* is to mimic the characteristics of a design that is eventually intended to have a different size as a finalized product. The objective hereof is generally to reduce resource allocation in cost or time but can also be rooted in practical restrictions. The concept of *virtual prototyping* is also represented in Figure 17 and concerns computational development and the testing of models.

The outlined prototyping objectives align well with those previously introduced as the purposes of prototyping and the general objectives of reducing cost and time of development.

### 3.5.3 Existing prototyping support tools

A limited number of prototyping support tools are available today. In a recent study in the research journal *Research in Engineering Design*, Menold et al. provided an initial overview of existing prototyping frameworks (2018). We have adopted and built upon that overview as illustrated in Table 8.

*Table 8: Overview of prototyping frameworks and their evaluated outcome. The table is an expansion of initial list provided by Menold et al. (2018). Asterisk (*) indicate references not provided in the initial list.*

| **Authors** | **Description** | **Outcome** |
|---|---|---|
| (Wall et al., 1992) | Prescriptive method for prototype manufacturing or processing decisions, based on prototype performance needed and time/cost drivers | Reduction in cost or time of prototype manufacturing (i.e., actually building the prototype) |
| (Thomke, 1998) (Thomke and Bell, 2001) | Optimal mode switching of prototype creation to increase experimentation efficiency | Reduction in time to market and engineering effort during NPD |
| (Moe et al., 2004) | Prescriptive prototyping strategy (e.g., parallel prototyping or serial) based on schedule, budget, and design flexibility inputs | Theoretically reduce the time and cost of prototyping, but not tested empirically |
| (Christie et al., 2012) | Heuristics for improved prototyping activities, based on expert designers | Improved technical quality and resource management |
| (Camburn et al., 2013)* (B. Camburn, 2015) | Prototyping strategies that provide practitioners with a systematic guide focused on the creation of prototypes | Improved final design performance |
| (Camburn and Wood, 2018)* | Prototype fabrication strategies based on open-source DIY online repositories | Improved technical quality and design performance |
| (Menold et al., 2018) | 'Prototype for X' supports a flexible prototype strategy incorporating human-centered design methods | Improved user satisfaction, user-perceived value, manufacturability of final designs |
| (Carlye A Lauff et al., 2018)* | Prototyping canvas inspired by business model canvas. Tool for simple prototypes during early stage design. Developed from action research in industry but no validation of tool performed. | Walks designers through assumptions and questions around the desirability, feasibility, and viability of aspects related to the problem space |

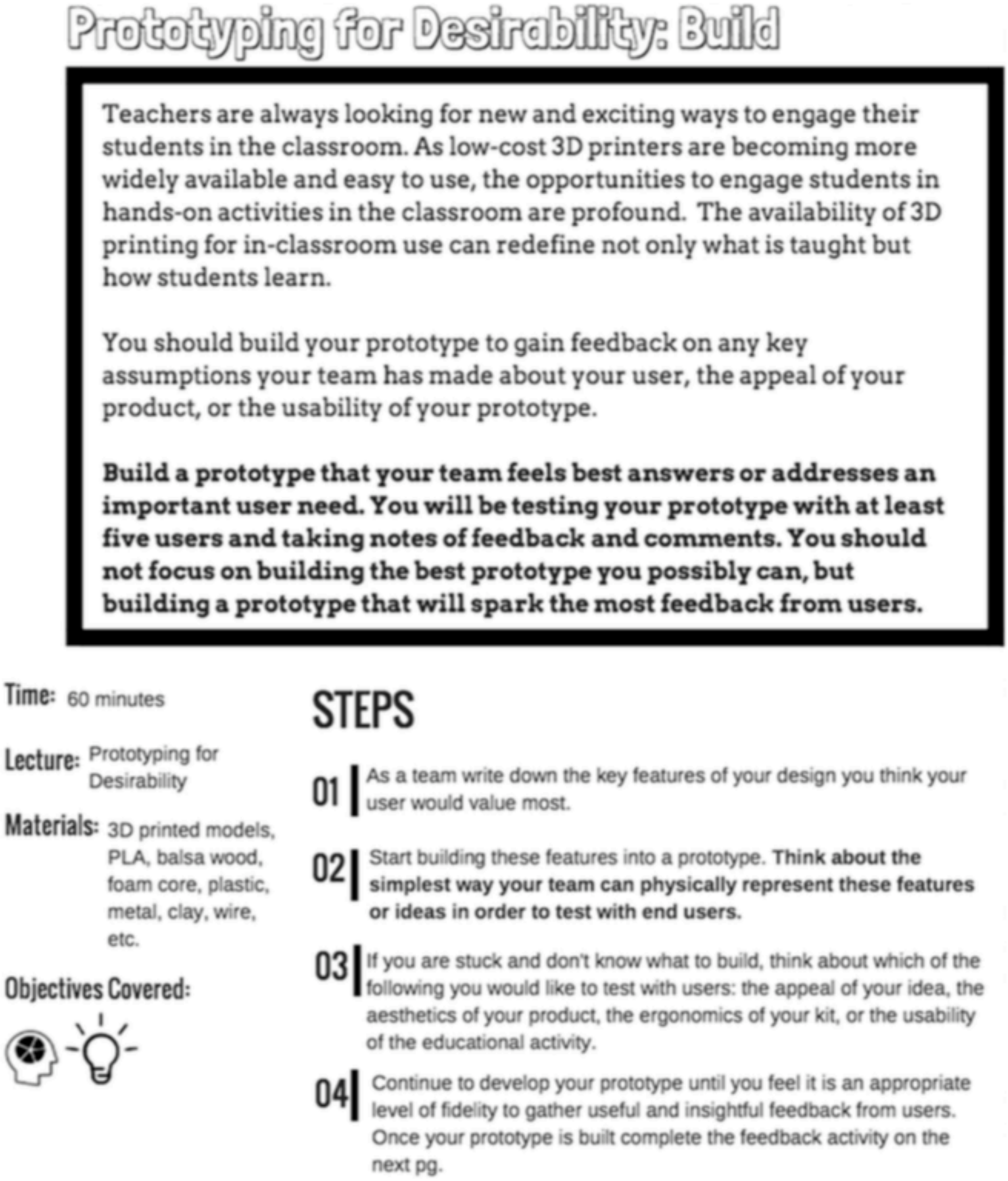
The tools outlined in Table 8 generally attempt to formalize observed design heuristics or principles of best practice into strategies or frameworks that can support prototyping effectiveness. Prototyping strategies have been defined by Christie et al as: “the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)” (2012). A tendency for these prototyping tools are that they either focus at optimization of recourse allocation in prototype fabrication, or that they are evaluated on performance assessment of design outcome from a narrowly defined design task. In the following paragraphs we introduce three of the most recent examples from Table 8, which also documents a research trend towards a broader focus of prototyping frameworks proposed by design researchers.

Camburn et al. have focused their work at the topic of prototyping strategies. An example of a hierarchical list of design decisions to determine a broad prototyping strategy is outlined in Figure 22, in which five overall categories are used to direct a range of design reflections (Camburn et al., 2013). The framework has been evaluated though focused experiments with students.

| | | |
|---|---|---|
| **Scale** | Scaled or actual boundary conditions/parameters | |
| | Scaled or actual function | |
| | Scaled or actual geometry (dimensions, shape, tolerances) | |
| **Integration** | Physical integration or segmentation/subsystem isolation | |
| | Functional integration or segmentation | |
| **Logistics** | *Allocations* | Rigid or flexible scheduling |
| | | Rigid or flexible budgeting |
| | *Make* | Number of design concepts (in parallel) |
| | | Number of iterations of each concept |
| **Embodiment** | COTS (Commercial Off-the-Shelf) or custom parts | |
| | *Material* | Actual or easy to manufacture |
| | *Material* | Ad hoc or precise (formal or systematic) |
| | Virtual or physical | |
| | Outsourced or in-house | |
| **Evaluation** | Relaxed or stringent parametric design requirements | |
| | Exploration or verification | |
| | *Testing* | Dynamic or static |
| | | Run conditions or failure conditions |
| | | Multiple test conditions or single condition |
| | | Continuous or discrete variation of parameters |

*Figure 22: Framework for broad prototyping strategy based on hierarchical decisions. Redrawn from (Camburn et al., 2013)*

Menold has proposed the “protoype for X” framework and published a series of articles focusing on different aspects of the framework and validations of its performance in student projects (Menold et al., 2018, 2017, 2016). A core principle of “prototype for X” is the adoption of *Design Thinking* and the three ‘lenses’ of desirability, viability and feasibility (Brown, 2009). Figure 23 illustrates a handout from the framework prescribing how to build prototypes focused on validating the desirability of a product.



Prototyping for Desirability: Build

Teachers are always looking for new and exciting ways to engage their students in the classroom. As low-cost 3D printers are becoming more widely available and easy to use, the opportunities to engage students in hands-on activities in the classroom are profound. The availability of 3D printing for in-classroom use can redefine not only what is taught but how students learn.

You should build your prototype to gain feedback on any key assumptions your team has made about your user, the appeal of your product, or the usability of your prototype.

**Build a prototype that your team feels best answers or addresses an important user need. You will be testing your prototype with at least five users and taking notes of feedback and comments. You should not focus on building the best prototype you possibly can, but building a prototype that will spark the most feedback from users.**

**Time:** 60 minutes

**Lecture:** Prototyping for Desirability

**Materials:** 3D printed models, PLA, balsa wood, foam core, plastic, metal, clay, wire, etc.

**Objectives Covered:**

STEPS

01 As a team write down the key features of your design you think your user would value most.

02 Start building these features into a prototype. **Think about the simplest way your team can physically represent these features or ideas in order to test with end users.**

03 If you are stuck and don't know what to build, think about which of the following you would like to test with users: the appeal of your idea, the aesthetics of your product, the ergonomics of your kit, or the usability of the educational activity.

04 Continue to develop your prototype until you feel it is an appropriate level of fidelity to gather useful and insightful feedback from users. Once your prototype is built complete the feedback activity on the next pg.

*Figure 23: Example of prototype for X handout for student projects from Menold et al. (2017).*

Finally, based on ethnographic studies of prototyping activities in three companies, Lauff et al. have proposed the “Prototyping Canvas” (Carlye A Lauff et al., 2018). This approach differs from the two aforementioned frameworks, as the tool was conceptualized through insights from industry rather than academic literature. The canvas is illustrated in Figure 24 and builds on the popular *Business Model Canvas* introduced by (Osterwalder and Pigneur, 2010) and the mentality from *The Lean Startup* by (Ries, 2011). At present no evaluation of the tool have been published.

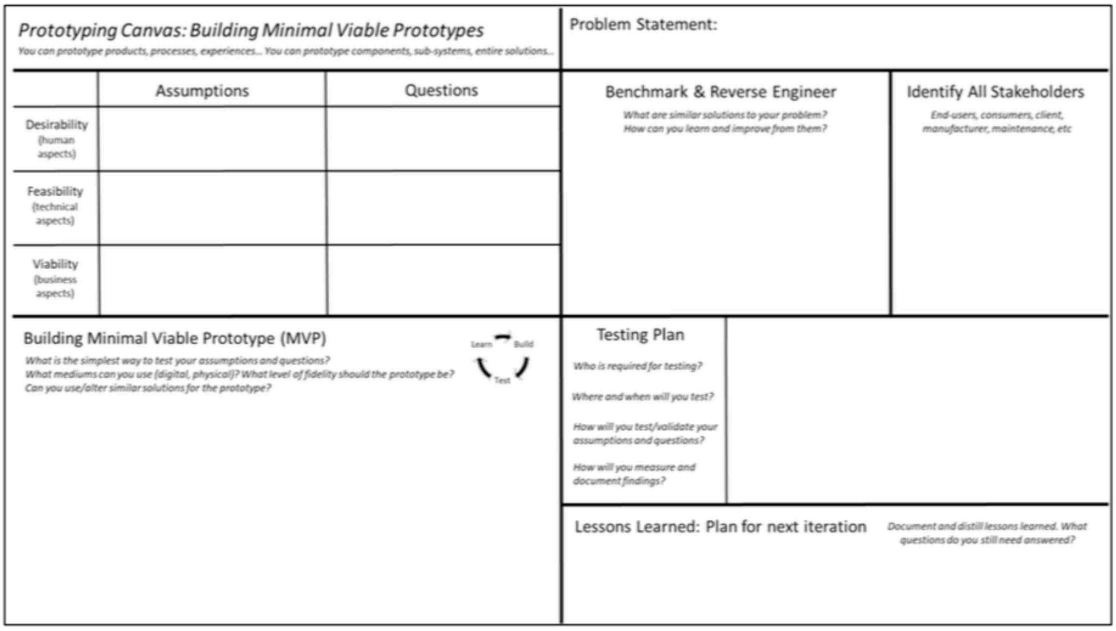



*Figure 24 Prototyping Canvas from (Carlye A Lauff et al., 2018).*

The increased attention towards prototyping frameworks in academia has helped to provide new insights and also indicates that there is an increasing interest in understanding the different aspects of prototyping in design.

### 3.5.4 Fabrication of prototypes

The tools and services available for prototype fabrication are constantly evolving. New technological achievements are one aspect thereof; another is the global rollout of concept such as FabLabs and makerspaces, which brings access to fabrication tools “to the masses” (Anderson, 2012; Lipson and Kurman, 2013). Such development along with associated digital ecosystems directly affects prototyping practice by reducing the unit cost of fabrication. Furthermore, at least three other impacts can be highlighted:

- *Digital fabrication technologies* - e.g., laser cutters and 3D printers – have become widely available. They provide new opportunities for the fabrication of physical and potentially advanced models (Jensen et al., 2016).
- *Reconfigurable electronics platforms* - e.g., the Arduino and Raspberry Pi - and their surrounding environments of digital components - provide wide opportunities

for bringing physical models "to life" with interactive and digital functionalities (Camburn et al., 2017).

- *Open sharing platforms* - e.g., Thingiverse, Github and Instructables – constitute a large ecosystem of digital designs, open-source software and guidelines that can support prototyping activities both in terms of inspiration or direct adaption of existing designs (Özkil, 2017; Camburn et al., 2015).

While the costs, time allocation and "barrier of entry" for prototyping in product development are generally lowering through this development, said development also brings new challenges. Wall et al. have argued that consequently the knowledge and skills of fabricators are overlooked and decision-making is centered around the designer (Wall et al., 1992). This development intensifies the need to support designers in their prototyping activities.

## 3.6 Physical Prototyping vs...

Today's designers have wide opportunities in prototyping, and essentially (almost) anything can be prototyped. This, however, does not mean that everything necessarily should be prototyped.

Buur has stated that "prototyping can be seen as a way of buying information about a future product" (1989). This statement entails the implicit meaning that prototyping is also associated with costs of resources (time and money) and is therefore not always the most optimal approach for an effective and efficient design activity. This observation goes well in hand with the statement by Abbas and Howard, "An experiment is worthwhile only if it increases the profitability of the decision more than it costs" (2015).

Alternatives to prototyping are opportunities such as sketching, calculations, simulations and CAD tools along with a range of emerging virtual possibilities, or simply just gut feeling. These alternatives are separate research topics of their own.

In this chapter we have introduced different perspectives on what defines a prototype as well as characteristics, applications and purposes of prototypes. This including two proposals for prototype taxonomies. Collectively this illustrates a broad understanding of what prototypes are, and also how their roles and purposes are perceived in product development activities. By introducing a theory for the prototyping process along with an overview of existing prototyping approaches and existing prototyping frameworks we draw the conclusion that the existing body of literature – despite a growing interest in the topic - only to a limited extend has focused on supporting the full prototyping cycle.

We will not unfold further theoretical perspectives, but rather refer to the references provided along the respective sections, or alternatively the appended papers which further elaborate on different aspects of the topics covered.

# 4 Results

*This thesis comprises six studies that have been published, or are undergoing peer review for publication, in scientific journals or peer-reviewed international conference proceedings. Further a draft, IR, presents intermediate results of 'work in progress' from 13 in-depth interviews with hardware start-ups.*
*The objective of this chapter is to highlight relevant results. Each section features a short motivational introduction, the relevant research questions, research methods, summary of results and contributions central to the dissertation and finally discussions and reflections.*

The work presented in this chapter presents knowledge documented as part of our project on prototyping in hardware start-ups. As previously mentioned in Chapter 1and illustrated in Figure 3, the results of our work can be categorized in three objectives.

The first objective is focused on *understanding design*. Here paper A, the draft IR, paper B and paper C aim at providing such insights and results that make it possible for us to answer our first two research questions i) how prototypes are defined and what their roles and purposes are in hardware start-ups?, and ii) what main product development challenges we can identify for hardware start-ups?

The second objective is to *explore design approaches*. Here, Paper D and Paper E both provide insights that contribute to answering our third research question on iii) how digital fabrication technologies can be utilized to support prototyping of consumer products developed by hardware start-ups?

The third objective is to provide support for designers with limited or intermediate experience. We do this through introduction and evaluation of the support framework, the Prototyping Planner, in Paper F.

## 4.1 Paper A

The objective of this study was to understand the purposes, strategies and definitions of prototypes in engineering design literature. This objective led to the following two research questions:

Paper A - Research Questions:

- RQ1: How are prototypes defined in engineering design literature?
- RQ2: What are the strategic elements of prototyping?

### 4.1.1 Publication

| | |
|---|---|
| Title: | PROTOTYPES IN ENGINEERING DESIGN: DEFINITIONS AND STRATEGIES |
| Authorship: | First Author |
| Conference: | 14th INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016, Dubrovnik - Croatia, May 16 - 19, 2016. |
| Citation: | Jensen, L.S., Özkil, A.G., Mortensen, N.H., 2016. Prototypes in engineering design: Definitions and strategies, in: DS 84: Proceedings of the DESIGN 2016 14th International Design Conference. |

### 4.1.2 Research methods

The basis of this study was a systematic literature review of prototypes in engineering design and product development literature. The Scopus database was used to perform the literature search, using "prototype" in combinations with the search terms “engineering design” and “product development.” The corpus analyzed consisted of 271 publications including books, proceedings and journal publications, and constituted the basis of the work presented in this paper.

### 4.1.3 Summary of Results

The results present 19 different definitions of the term ‘prototype’ found in the literature. To clarify their relation to specific stages of product development and illustrate overlapping elements of these definitions, we propose five prepositions to categorize and group the 19 definitions. This categorization is illustrated in Figure 25.

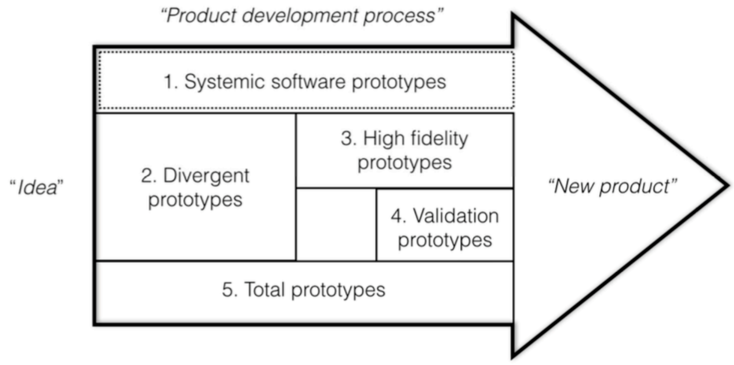



*Figure 25: Graphical illustration of five prepositions to categorize prototype definitions.*

In the bullets below we elaborate on this categorization:

- *Systemic Software Prototypes*: This category of definitions originates from software engineering-related publications. They represent systemic thinking and emphasize that prototyping activities with both partial and whole systems can take place. Such openness in scope and design stage relation is illustrated by the dotted enclosure in Figure 25.

- *Divergent Prototypes*: These definitions include a clearly divergent interpretation of prototypes. This category is opposed to the majority of definitions, which are oriented towards prototypes as convergent tools with a concluding nature. As the exploratory elements of product development are often concerned with the early design stages we link this group to the initial stages of the development process.

- *High fidelity prototypes:* These definitions generally imply that a prototype is concerned with some aspect of testing and also imply a prototype to include a certain level of complexity and maturity. We categorize these to generally relate to the later stages of product development.

- *Validation prototypes*: This group defines a prototype as a mature model of a product before commitment to production is made and represents a rather narrow understanding of prototypes.

- *Total prototypes*: This group concerns an understanding by which every model representing a product or idea can be referred to as a prototype.

A second part of the review outlines different purposes of prototyping and categorizing of literature that deals with strategic elements of prototyping.

#### 4.1.4 Discussion and Reflections

From this review, we conclude that the term *prototype* is used very broadly and that no overarching understanding seems to exist. Furthermore, there seems to be no overview or systemic categorization of the reported purposes of prototyping, existing definitions and collective strategic prototyping knowledge in design. With such observations perspectives could be drawn to the more comprehensive work done by McMahon on identifying and characterizing the wide diversity of the design research community (2012). Here it is argued that the wide diversity calls for work to consolidate the topic. By reviewing a substantial body of literature, we establish an overview of how prototypes are understood in academia. A hypothesis is that discrepancies might exist, however, when comparing this understanding to industrial practice.

## 4.2 Draft IR: Intermediate results

The objective of this study is to understand the roles and purposes of prototypes in hardware start-ups. The work presented in this section is a representation of ongoing works in progress. The study is intended for future publication after further analysis, documentation efforts and alignment with state-of-the-art literature. The research questions defined for the study were the following:

| Draft IR - Research Questions: |
| --- |
| RQ1: What are the roles and purpose of physical prototypes in hardware start-ups? |
| RQ1.2: How do hardware start-ups fabricate prototypes? |
| RQ1.3: How are prototypes exposed (used) by hardware start-ups? |

### 4.2.1 Draft

| | |
| --- | --- |
| Title: | A study of the role and purposes of prototypes in 13 hardware start-ups |
| Authorship: | First Author |
| Publication: | Not yet submitted for publication |

### 4.2.2 Research methods

This study was based on semi-structured interviews with 13 hardware start-ups in Denmark (7), Sweden (2) and China (4). The study participants were selected due to their focus on consumer hardware. Our interviews focused on five overall topics, around which our interview protocol was developed:

- General company information.
- Interviewee and team backgrounds.
- Product development approach.
- Perception of prototypes and prototyping.
- Prototyping processes and activities.

Five of the interviewees held more than five years of post-graduate professional experience and eight did not.

### 4.2.3 Summary of Results

Through the 13 interviews conducted, we find that the start-ups teams mainly defined prototypes very broadly and in a way that aligned with the notion of *total prototypes* introduced in our previous literature study. A remaining group of three start-ups presented definitions that can better be characterized as *high fidelity models* (appended Paper A).

From coding the interviews into five overall themes and 14 sub-themes, we further found that prototypes serve many roles and purposes for the development teams.
An important understanding obtained was that roles and purposes of prototypes are dynamic and also sometimes hierarchical. Prototypes might originally be fabricated or

ordered to test or learn about a certain design aspect, but later be used for other purposes, such as communication with the design team.

The study further helped to clarify that the start-up teams were not making use of any design-rooted support tools for the prototyping process. The teams argued to draw on their experience, and for specific fabrication tasks, they followed online guidelines to support fabrication activities.

From the interviews emerged a range of observations and patterns, that we in their combination do not find well expressed in the existing literature. These described and articulated by six design teams in particular. These teams were all part of the group which described their definitions of prototypes very broadly, and reported particularly active use of prototypes for their design activities. We aim at summarizing our observations in six characteristics:

- Prototyping is the designer's "weapon of choice" and language of expression.
- Design propagates from prototype to prototype, and prototypes serve various purposes.
- Prototypes facilitates increased *product understanding*, *version control mechanics* and *richer collaboration*.
- Prototypes function as boundary objects to mitigate uncertainty and personal bias in decision-making.
- Prototyping is a catalyst for codifying and transferring tacit knowledge.
- Designers utilize opportunities of digital fabrication and DIY design repositories as well as manufacturing services.

In their combination these characteristics describe start-up organizations which have a particular prototyping focused development culture. As this practice was identified among six of the 13 design teams, we should be aware that there are some restrictions regarding the generalizability of our findings.

#### 4.2.4 Discussion and Reflections

From this study we identified two of the five categories that in our previous study were introduced to describe different prototypes' definitions (appended Paper A).
The study further documents an active and broad use of prototypes by hardware start-ups. In particular among six design teams we identify a prototype driven development culture. We find that this study provides two primary insights for this project:

- Prototypes take up a central role in the development process of hardware start-ups and underline the importance for engineers to develop prototyping competencies.

- That designers mainly rely on experience, and only use guidelines on fabrication to support prototyping activities, is not necessarily an implication for the design activities. However, such fabrication guidelines do presumably not support the designer in the full prototyping cycle. This leaves out metrics such as scoping or formulating design questions, or the definition of the appropriate approach for testing or using the prototype. When reminding that the majority of interviewees held less than five years of experience their prototyping efforts could potentially increase in quality and efficiency from dedicated prototyping support.

## 4.3 Paper B

Reward-based crowdfunding platforms have become widely popular and made product realization available for a wider audience. Crowdfunding platforms can also be considered rich data libraries of product development cases. Such platforms can be used to investigate and understand the challenges associated with product development in hardware start-ups. In this light, the objective of this study was to answer the following research questions:

Paper B - Research Questions:

- RQ1: What product development issues are reported by campaign initiators of successfully funded reward-based crowdfunding campaigns as causes for failing to deliver on their promises?
- RQ2: How do backers evaluate rewards from campaigns that also developed and shipped their products in terms of promised features and product quality?
- RQ3: To what extent can particular product development implications or relations between RQ1 and RQ2 be identified as a cause for failure?

### 4.3.1 Publication

| | |
|---|---|
| Title: | Identifying Challenges in Crowdfunded Product Development: A review of Kickstarter Projects |
| Authorship: | First Author |
| Journal: | Design Science Journal |
| Citation: | Jensen, L.S., Özkil, A.G., 2018. Identifying Challenges in Crowdfunded Product Development: A review of Kickstarter Projects, Design Science Journal Vol.4 e18. |

### 4.3.2 Research methods

Our study is based on data collected from 144 reward-based crowdfunding campaigns that ran on Kickstarter.com. All campaigns focused on consumer hardware and 69 of them managed to deliver products. Our objectives were to explore and understand the product development challenges for hardware start-ups that obtained financial backing through crowdfunding. To analyze these challenges in a systematic fashion, we first developed a failure mode model through analysis of 30 campaigns, and then used the model to benchmark 114 campaigns. The overall process of the study is outlined in Figure 26.

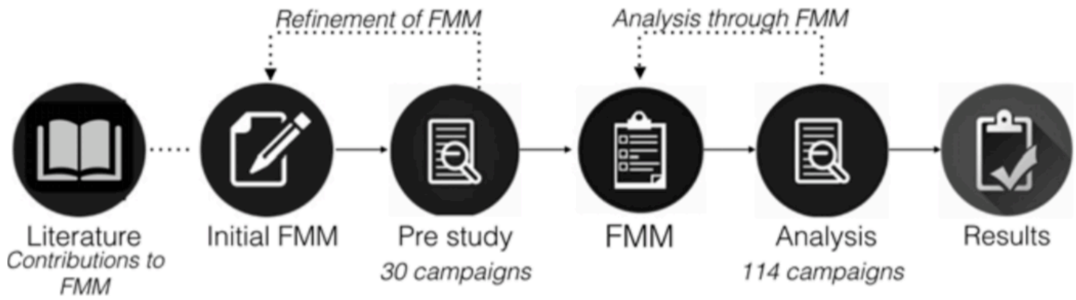



Figure 26: Workflow of study conducted in Paper B

The empirical material analyzed for this study included campaign material provided by project initiators, comments from backers and ongoing project updates by initiators.

### 4.3.3 Summary of results

This study investigates the phenomenon of *crowdfunded product development*, which we define as the product development project taking place in the context of a crowdfunding campaign. Here, we respectively identify and quantify: i) issues that occur during the product development process and ii) issues regarding the delivered products reported by the campaign backers.

The study reveals that no more than 32 percent of the campaigns delivered products on time, according to preannouncements. Our analysis further reveals that, if campaigns are delayed, there is a significantly higher probability that the delivered products might lack expected and announced attributes, such as product features. Finally, the causes for delay can have many reasons, but particular issues were identified as the main challenges. We identified that five failure modes were significantly more often reported for campaigns that had been delayed:

- The product is lacking preannounced and expected features.
- The product does not live up to expected levels of usability.
- The teams identify Design for Manufacturing deficiencies on the mature design.
- The team faces manufacturing quality issues, either from manufacturing processes not meeting expectations or a product design that is not suitable for selected manufacturing processes.
- The team faces management challenges related to their own organization and internal administration.

Because of their significant occurrence, we find that these five challenges are important characteristics to focus on when supporting hardware start-ups in their design activities. Further, one of the overall consequence of these challenges is delays in product launch, which should not be underestimated as an overall challenge.

#### 4.3.4 Discussion and Reflections

While different approaches can be applied to mitigate the product development challenges identified in this study, we argue that rigorously prototyping design concepts is one - of multiple - suitable design activities. Our previous study (draft IR) indicates that even management challenges could to a certain extent be mitigated through prototyping. This by improved communication and codification of inherent tacit knowledge for the design team. From this study we cannot present any relationship between the extent of prototyping activities and the identified product development challenges. The reputable manufacturing and design consultancy Dragon Innovation have though highlighted *lack of prototyping* as one of the top ten reasons why hardware start-ups fail ("Dragon Innovation," 2016).

In section 1.1 we outlined that this project focuses on the product development stages before manufacturing. This study could seem contradictory as it reports on topics such as manufacturing challenges. However, to understand the potential later consequences of 'non-optimal design decisions' made in early stage product development also feeds into this project scope. This study hereby provides an important quantitative understanding of product development challenges that can hinder the success of hardware start-ups. These challenges are important to understand for researchers working on future support tools dedicated to such start-up teams.

This study uses crowdfunding campaigns as a proxy to study challenges in hardware start-ups. A restriction for the generalizability to other start-ups, is that crowdfunding mechanisms might introduce special characteristics compared to other funding schemes. There might e.g. be a particular incentive to oversell both one's own and the product's abilities to maximize campaign funding. There may also be a potentially higher uncertainty in establishing manufacturing partnerships, as it is not initially known how many units to fabricate. Further evaluations are required to clarify any such discrepancies between the challenges encountered by start-ups who obtained funding through a crowdfunding platform and those who used more conventional funding schemes.

## 4.4 Paper C

Through in-depth interviews with nine hardware start-ups, who had all completed successful crowdfunding campaigns, the motivation of this study was to provide qualitative insights on product development in hardware start-ups. This motivated the following research questions:

> Paper C - Research Questions:
> - RQ1: How are teams in crowdfunded product development composed?
> - RQ2: Which design methodologies are known and used in the design process of crowdfunded products?
> - RQ3: What particular characteristics of crowdfunded product development can be identified?

### 4.4.1 Publication

| | |
|---|---|
| Title: | Crowdfunded Product Development: A study of hardware start-ups |
| Authorship: | First Author |
| Journal: | Undergoing review for journal publication |
| Citation: | n/a |

### 4.4.2 Research methods

This study was based on in-depth semi-structured interviews and campaign data that were extracted from crowdfunding platforms. The study participants were selected for their focus on consumer hardware, and interviewees had main development responsibilities. Our interviews focused on five overall topics, around which our interview protocol was developed:

- General information on the company.
- Interviewee and team backgrounds.
- Crowdfunding campaign and outcome.
- Product development and crowdfunding.
- Design methodologies in product development

### 4.4.3 Summary of results

This study had three objectives. The first was to understand characteristics of product development for start-ups that have run crowdfunding campaigns. The second, is to understand the composition of start-up design teams. And the third, is to understand what methodologies that the design teams respectively know and adopt.

The study identifies five characteristics of crowdfunded product development. In combination these characteristics indicate quite different approaches to running a campaign. We e.g. show how campaigns were run with a perceived product design maturity varying from 5% to 80%, at the time of campaigning. Also wide diversity in timeliness is observed, ranging from 2 weeks' delay in product delivery to 13 months, at the time when the interview was conducted. On average the teams were six months delayed in delivering products to their backers.

Our study reveals that most start-up founders (34) have technical backgrounds, either because they have formal engineering degrees (17) or they became technical experts by trade (2). Only three of the nine teams include members with more than five years of product development experience.

We further find that the presence of experienced team members – with over five years of experience - influences the start-ups' ability to deliver products on time. On average products are only delayed for half a month if the team includes experienced engineers.

Our last focus is on understanding the *knowledge of* and *use of* design methodology. We generally find that the teams make little use of design methodology despite some awareness of existing tools.

Six out of twenty methodologies presented were unknown to the interviewees, and four of them were only heard of but not used. The interviewees had varying experiences with the remaining ten methodologies. Methodologies that originate from business or software domains – *The Lean Start-up* (Ries, 2011), *Business Model Canvas* (Osterwalder and Pigneur, 2010), *Agile development* and SCRUM (Takeuchi and Nonaka, 1986) - were the most widely known methods, whereas the remaining methodologies had intermediate levels of domestication among the start-ups.

#### 4.4.4 Discussion and Reflections

This study helped us understand more general aspects of product development for hardware start-ups. The study should be considered exploratory and the sample size also determines that results not necessarily generalizable to all hardware start-ups.

While different viewpoints and opposing reports on the adoption of design methodologies from different industries exists (Chakrabarti and Lindemann, 2015; Andreasen, 2011; Araujo, 2001), there is only very limited information on what tools and methods are used by hardware start-ups. Through this study we document that the adoption of methods is generally limited to 'block-busters' like *the Lean Start-up* and *Business Model Canvas*.

Essentially, it can be discussed whether it is good or bad that the teams did not adopt the conventional design methodologies and process models, which might not be suitable for the dynamic and uncertain development context of hardware start-ups.

From the literature we do though know that in non-routine situations, design methods can elevate the performance of inexperienced designers (Daalhuizen and Badke-Schaub, 2011). Hereby the majority of the start-up teams (6) (where all team members had less than five years of experience) might benefit from suitable design support dedicated hardware start-ups. This as the inexperienced teams are more likely to face delays in their development projects.

In conclusion, crowdfunding might be lowering the barrier of entry for entrepreneurs in the hardware domain, and inexperienced design teams are developing products widely without the use of design support. This study indicates an existing need for supporting designers with tools meant for the development context of hardware entrepreneurship, e.g. by having a central focus on prototyping to help mediate uncertainty.

As with the work presented from paper B, a restriction on the generalizability of these findings is that crowdfunding might introduce special characteristics that affect the development process of the hardware start-ups.

## 4.5 Paper D

The results presented in this and the following study differ from those presented until now in this thesis, as they were conducted in collaboration with two start-up companies, and concerns a specific case. This case, in both companies, serves to investigate a particular aspect of prototyping.

When developing consumer products, it is often essential to expose prototypes to potential users to collect feedback on various design aspects. A critical question is what fidelity and resolution of prototypes to use, and how such can affect feedback from users. With the objective to contribute to this understanding, this study aimed to answer the following research question:

> Paper D - Research Question:
> - RQ1: How does the fidelity of prototypes (representing a mechatronic concept) affect test users' perception of a concept?

### 4.5.1 Publication

| | |
|---|---|
| Title: | PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT |
| Authorship: | First Author |
| Conference: | 15th INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018, Dubrovnik, Croatia |
| Citation: | Jensen, L.S., Nissen, L., Bilde, N., Özkil, A.G., 2018. PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT. Presented at the 15th International Design Conference |

### 4.5.2 Research methods

This study was conducted in collaboration with a start-up company developing a mechatronic padlock. During the conceptual development stage, feedback from test users was collected by utilizing four different prototypes at different stages of fidelity. The prototypes are presented in Figure 27, and only one prototype was introduced to each of the 66 participants. All participant was surveyed from an identical interview protocol. The protocol focused on participants' understanding of the padlock concept and perceived utility, usability and desirability.

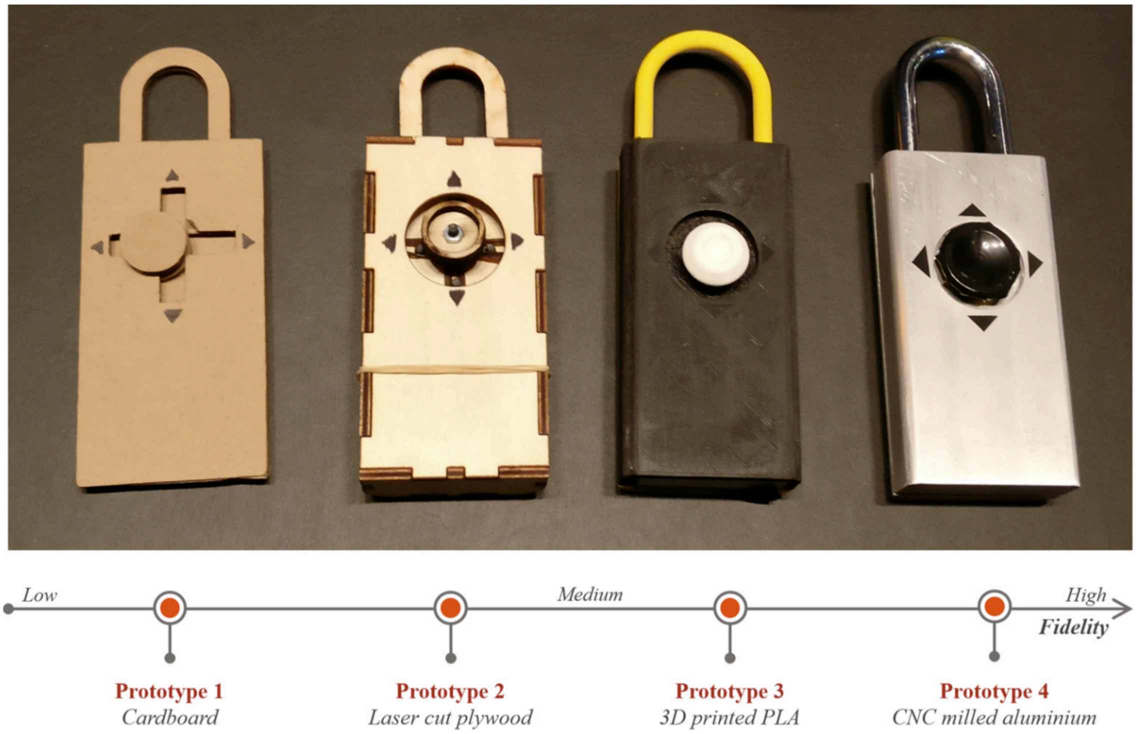


*Figure 27: Picture of prototypes used for study including process bar illustrating increasing fidelity*

### 4.5.3 Summary of results

The digital fabrication tools available for prototyping are constantly evolving, and it can be a challenge for designers to identify the most optimal balance between fidelity and effective prototyping (Schmidt et al., 2017).

From this study we find that prototype fidelity influences how the concept is perceived by test users. Our findings include:

- When evaluating how the utility of a concept is perceived, too many functions incorporated in the prototype can introduce noise, which may remove focus from the particular aspect of the product design on which the designer seeks feedback. Also, unintended functionality of a prototype, as a rotatable knob on prototype 2, can result in incorrect interpretations of concept functionality.
- In terms of usability, our results suggest that low-fidelity prototypes are (resource) effective tools in understanding the needs of test users. There is a 1:400 cost ratio and a 1:20 ratio in fabrication time between Prototype 1, made of cardboard, and Prototype 4 of CNC milled aluminum. Balancing the resources spent with the design insights obtained, underlines that low-fidelity prototypes are valuable and allow for a larger number of design iterations within the same budget constraints in terms of both time and costs.

As part of our study we recommend that practitioners carefully plan their prototyping activities. Part of this process can include the following four heuristics:

- The design questions should drive what design medium can be utilized for a prototyping activity. When it is possible to utilize low-fidelity prototypes, we

recommend that resources are allocated to a large number of low-fidelity prototype iterations over a few high-fidelity iterations.
- To conduct fast pre-studies to verify that the exposed prototypes are perceived as intended.
- To consider the inclusion of more than one type of prototype to obtain more varied feedback.
- To collect a combination of qualitative and quantitative data for varied results.

#### 4.5.4 Discussion and Reflections

A prerequisite for designers to establish well-founded prototyping strategies is that the designer either possess or have access to a knowledge on prototyping to provide adequate guidance for decision-making.

This study contributes to our understanding of prototyping activities in this research project, but also provide valuable insights that can help practitioners determine the appropriate prototype fidelity. This is highly relevant as a key objective for efficient prototyping is to obtain sufficient insight to progress the design project with minimum expenditure in terms of time and cost (Otto and Wood, 2003).

Our findings support the existing body of literature underlining the value of low-fidelity prototypes for interactions with potential product users. In the domain of digital fabrication, such results are of relevance, as diligently distributed marketing material from machine manufacturers could make designers believe otherwise. By primarily showcasing advanced capabilities of prototyping tool they indirectly suggest such as a best practice for product development activities (3D Systems, Inc., 2018; Stratasys Ltd, 2018).

To our knowledge, this is the first study to explore this topic while solely focusing on physical prototypes. For this research project the results of this study are further valuable as they constitute a foundational insight for the following Paper E, which draws on using low-fidelity prototypes like the ones introduced in this study.

## 4.6 Paper E

Through e.g. digital fabrication the cost of unit manufacturing for prototyping has vastly declined (Camburn et al., 2017). Such developments open for different approaches to hardware prototyping. The objective of this study was to explore if the concept of *Design of Experiments* could successfully be applied in early stage product development and lead to new data-driven insights. The study was conducted in the context of the following research questions:

Paper E - Research Questions:

- RQ1: How can DoE support prototyping in early stage product development, by identifying interactions, sensitivity and optimum values of design parameters driving user desirability?
- RQ2: What strengths and weaknesses can be identified when interlacing prototyping and DoE principles to optimize design parameters for user desirability in early stage product development?

### 4.6.1 Publication

Title: PROTOTYPING FOR DESIRABILITY BY DESIGN OF EXPERIMENTS: A CASE STUDY OF A HARDWARE START-UP

Authorship: First Author

Conference: ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference

Citation: Jensen, L.S., Vorting, D., Villadsen, A., Molleskov, L.H., Ozkil, A.G., 2018. Prototyping for Desirability by Design of Experiments: A Case Study of a Hardware Startup, Proc. Asme Int. Des. Eng. Tech. Conf. Comput. Inf. Eng.

### 4.6.2 Research methods

This study was conducted in collaboration with a hardware start-up. The team is working on the development of an anti-theft alarm device that can be attached to different objects. 14 physical low fidelity prototypes of the alarm system were built, in which variation was introduced in four core design parameters. In total, the prototypes represented 37 different product configurations. An example of the prototypes can be seen in Figure 28.

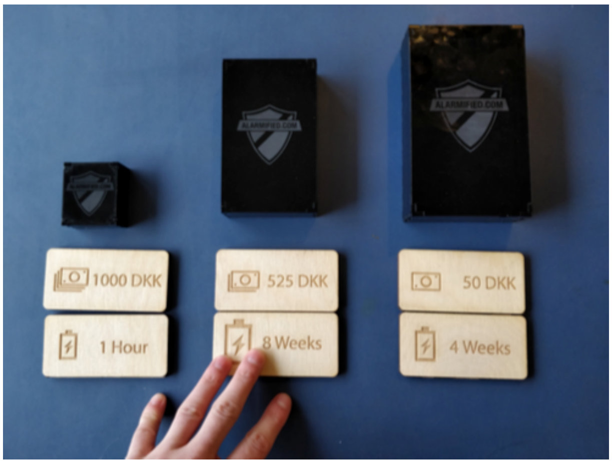



*Figure 28: Illustration of three prototypes used for the study.*

By utilizing the prototypes, tests with 44 potential users were performed, focusing on perceived desirability of the product. The specific composition of the prototypes and number of tests to be conducted were determined by following a *Design of Experiments* (DoE) layout, and results were continuously adapted and modelled in the software tool SAS JMP.
The collected results collectively constitute a statistical model, which describes optimum values and interactions of 4 design parameters. A small-scale verification of the model was performed with 7 users.

#### 4.6.3 Summary of results

This paper presents how prototyping and DoE principles can be combined and applied in the early stages of product development. The study explores how four selected design parameters affect and drive the perceived desirability of a physical alarm device. Essentially, the objective is to aid decision-making for the product design though a data-rich approach.

The research was conducted in a seven-step process. The steps respectively concern:

i) Identification, selection and modelling of relevant test parameters.
ii) Establishing the statistical model for the study.
iii) Fabricating prototypes based on the statistical model.
iv) Design of the experiments to be conducted.
v) The concrete execution of the user tests and collection of data.
vi) Analysis of the data to generate results.
vii) A verification of the established statistical model.

The seven-step process is presented in more detail in the original manuscript and is considered the main result of the paper, in which the case serves to illustrate the process and verify its consistency.

First of all, the results of the study show that the statistical model performs on par with comparable studies. A $R^2$-value of 0,69 is obtained along with an RMSE of 0,7717, where $R^2$ describes how well the graphical/mathematical model approximates the dataset obtained through the experiment. RMSE is a measure of the differences between the desirability values predicted by the model and the ‘actual desirability.’

Through the model it is possible to highlight the primary drivers of product desirability as well as exemplify the dynamics among the explored parameters. As product development often requires different compromises, it can be highly attractive to understand the dynamics and sensitivity of the design parameters in more detail. Figure 29 exemplify how the dynamics of the model can be explored in SAS JMP’s prediction profiler tool.

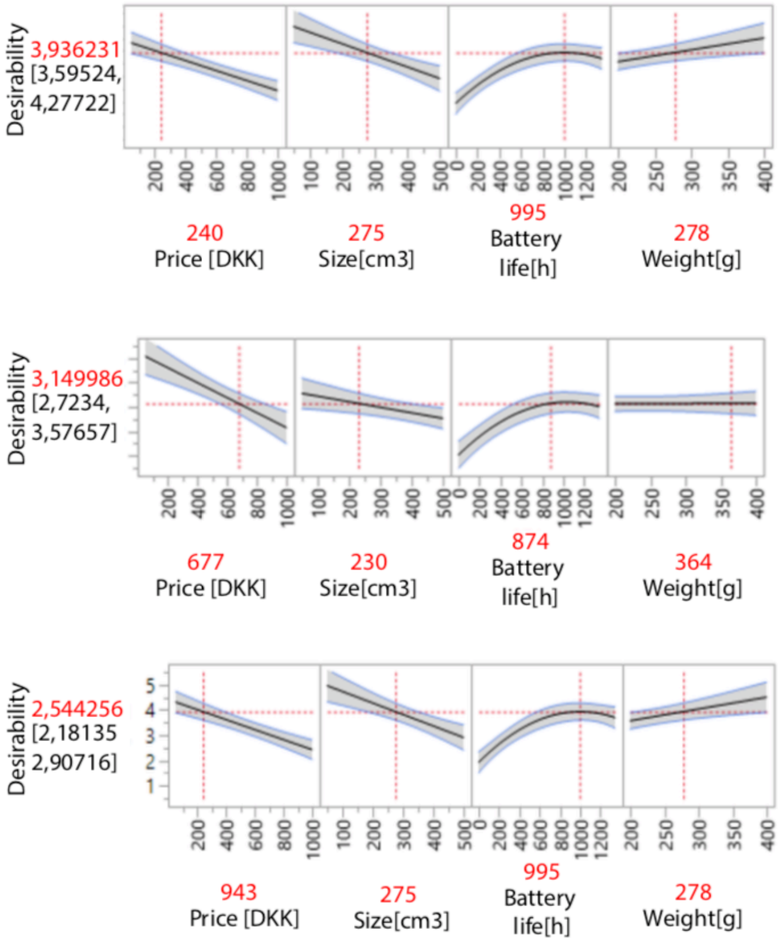



*Figure 29: Graphical illustrations of the four design parameters and illustration of their dynamics in relation to desirability.*

To verify the obtained model’s ability to prescribe the perceived desirability for specific prototypes of the alarm device, a small validation was performed.

The results of the verification experiment indicate that the statistical model can be used to predict user desirability ratings. Despite a small sample size of seven participants, the previously identified RMSE of 0.7717 demonstrates that the average rating of the verification test is well within the statistical model’s error margins.

### 4.6.4 Discussion and Reflections

An important enabler for this study is the recent advancements in prototyping tools and platforms utilized for the rapid fabrication of prototypes. The results of this study support the idea that a DoE approach can be used for user tests to identify design parameters that drive desirability. The seven-step process is the main contribution of the study, as it prescribes how to apply DoE in a hardware context.

Exceeding what has been presented in this study, there could be wide opportunities in further exploring the dynamics and sensitivity of design parameters through prototyping. These opportunities could include:

i) How to optimize desirability in combination with maximum profitability through identifying specific saddle point region in the response values.

ii) To apply the DoE approach when identifying qualitative ‘soft’ user preferences and translating them into quantified engineering requirements and specifications.

Finally, the start-up team argues that the product development insights obtained through this study were worth the invested effort in time and resources - 80 hours (40 hours for two developers).

## 4.7 Paper F

Through the accumulated insights obtained throughout this research project and specific needs identified in the existing literature, this study proposes and evaluates a prototyping framework named the Prototyping Planner. The framework is focused at supporting the full prototyping cycle ranging from design question to the resultant answers. For the study we defined the following research questions:

Paper F - Research Questions:

- RQ1: How does the introduction of a prototyping framework affect the perceived product development process of design teams?
- RQ2: How does the introduction of a prototyping framework affect the extend of best practice prototyping principles being performed by design teams?

### 4.7.1 Publication

| | |
|---|---|
| Title: | Fostering Prototyping Mindsets: Towards the framework Prototyping Planner |
| Authorship: | First Author |
| Journal: | Submitted for peer review for journal publication |
| Citation: | N/A |

### 4.7.2 Research methods

This study introduces the prototyping framework the Prototyping Planner. An initial layout of the framework is conceptualized by the authors, with offset in observations from this PhD project and a literature study. Further refinement and validation of the framework is performed through a workshop with five industry practitioners. This leading to the current layout of the framework.

The current layout of 'the Prototyping Planner' is then evaluated through a design challenge with 20 design teams distributed in two samples, where only one group were supported by the framework. The effects of the framework are evaluated by respectively surveying study participants on the perceived effect of the framework, and by comparing a set of prototyping best practice principles documented in build logs of all design teams.

### 4.7.3 Summary of results

The design challenge presented in this study concerns the design and fabrication of fully functional wireless loudspeakers. The study was conducted as a controlled experiment where 10 design teams had the opportunity to use the Prototyping Planner and 10 teams were not introduced to the framework. The framework is illustrated in Figure 30 below.

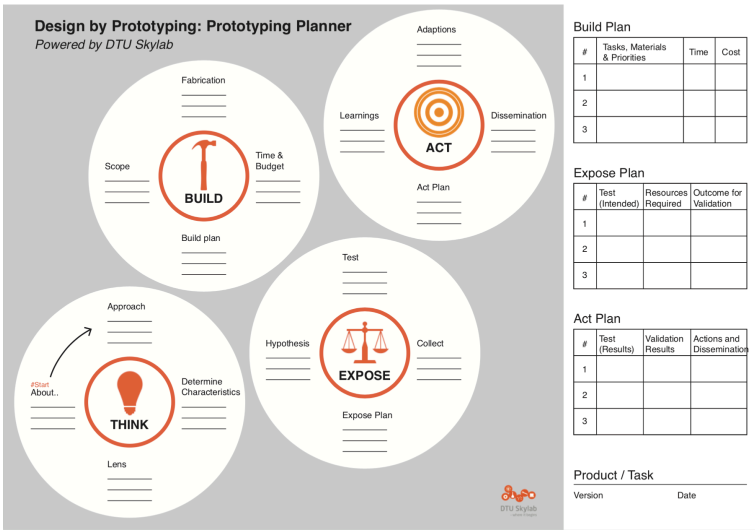



*Figure 30: Layout of 'the prototyping Planner'. Full size version presented in the original paper*

The study reveals that the majority of participants found the framework layout appealing and also that they were supported in obtaining a 'mindset for prototyping'

When evaluating the effects of the framework, the sample of design teams which had the opportunity to use the Prototyping Planner showed significant improvements in the design team's application of prototyping best practice principles. In particular four best practice principles were evaluated more often. The first concerns the ability to use prototypes of adequate fidelity and resolution, and the second to use them effectively on a focused/specific deign question. The last two concerns using inexpensive prototypes early and efficiently, but also to use readily available objects and materials for simple prototyping.

Despite these positive results, a range of opportunities for improving the framework are also identified. The survey with participants using the Prototyping Planner e.g. reveals that the metrics of the framework was not to a satisfactory extend able to support the design teams in topics such as decision-making and problem definition. Through coding of qualitative feedback from the participants it is further identified that e.g. inspirational examples on best practice, and more guidance on mode of action, was often requested by the participants.

### 4.7.4 Discussion and Reflections

The discussion of this study includes reflections on positive and 'negative' evaluation of the Prototyping Planner. One of the main themes discussed are how identified issues could be used as offsets for improvement on e.g. decision-making and problem definition. The observation that a range of participants specifically requested more examples of prototyping best practice is one example hereof. This lead to the hypothesis that novice designers could strengthen their understanding of both decision-making and problem definition in prototyping through the availability of more examples e.g. in a 'reference book'. For more general design methods such 'reference books' exists e.g. in *The Delft Design Guide* (Van Boeijen et al., 2014).

Further it is considered if ‘the mode of action’ of the framework could be improved and that a ‘digital native’ version might serve communication and collaboration aspects of the design process better. Also, we present reflections on why some participants to a wider extend than others choose to adopt the framework for their project.

Based on our obtained insights from this study, we underline that the Prototyping Planner is still a work in progress design framework, and should undergo further development before adoption are recommended.

Finally, in Section 3.5.3 we provided an overview of existing support tools for prototyping. Here we argued, that there is a current research trend towards a broader focus of the prototyping support proposed by design researchers. We perceive that the Prototyping Planner is only distantly related to these tools, with exception of *the Prototyping Canvas* (Lauff et al., 2018). Here similarities can be observed e.g. in the intention to comprehend the full prototyping cycle. Compared to the Prototyping Planner the metrics of the canvas are less detailed and has less focus on e.g. prototype fabrication. To date, no evaluations of the canvas has been published but while Lauff has not focused her work on hardware start-ups, we seem to have identified similar needs for holistic prototyping support that covers the full prototyping cycle.

# 5 Conclusions

*This chapter presents the conclusions for this research project and thesis. We start the chapter by providing answers for our research questions. Next, we highlight our main contributions and discuss the value and impact of our work. The third section of the chapter outlines research limitations and restrictions, and we finalize the chapter with main suggestions for further work on this research topic.*

This PhD project has focused on prototyping in hardware start-ups.
The research studies conducted as part of the project were overall structured according to the DRM by Blessing and Chakarbarti, and also sought to focus at three project objectives.

The first objective focused at understanding prototyping and product development in hardware start-ups. The topic was studied through the academic literature, and through qualitative as well as quantitative research methods to understand industrial practice.

The second objective explored how digital fabrication tools can be utilized by hardware start-ups for prototyping of consumer products. Two studies were conducted in collaboration with hardware-start-ups. These further developed our understanding of how hardware start-ups work and develop products, and also lead to respectively four design heuristics and a seven-step approach for interlacing DoE and prototyping of consumer hardware products. Collectively these first two objectives constitute the descriptive part of this project.

Based on our accumulated insights and identified gabs in literature we, as our third objective, proposed and evaluated the framework the Prototyping Planner. We intend for the framework to support novice designers in defining, building, testing and reflecting on their prototyping activities. The proposal and evaluation of the Prototyping Planner also constitutes the prescriptive part of this project.

In the next section, we provide answers to the four research questions outlined in Chapter 1 of this thesis.

## 5.1 Answering the research questions

**RQI: a) How are prototypes defined in literature and b) what is their role and purposes in hardware start-ups?**

Our results for answering this research questions draws primarily from two of our studies. Respectively, Paper A and our draft IR outlining intermediate results.

Through our literature review (paper A) we identified 19 definitions of prototypes in engineering design and product development literature. To better understand these definitions, we classified them into five groups, namely; *systemic software prototypes, divergent prototypes, high fidelity prototypes, validation prototypes* and *total prototypes*.

By interviews with 13 hardware start-ups (Draft IR), we found that ten of the 13 interviewees defined prototypes similar to the category of *total prototypes* identified through the literature review. This view defined prototypes very broadly; according to this definition, every model representing a product or idea can be referred to as a prototype. The remaining three interviewees presented more 'traditional' engineering definitions, in which prototypes are characterized by a *high fidelity* and are intended for testing.

From coding the interviews, we identified that prototypes are serving at least14 different roles and purposes distributed over the overall categories *Build/test, Functionality, Decision making, Communication* and *Learning.*
We further identified that in particular six teams reported prototyping as their central design tool. To encapsulate this rich use of prototypes we summarized our observations in six characteristics:

- Prototyping is the designer's "weapon of choice" and language of expression.
- Design propagates from prototype to prototype, and prototypes serve various purposes.
- Prototypes facilitates increased "product understanding," version control mechanics and richer collaboration.
- Prototypes function as boundary objects to mitigate uncertainty and personal bias in decision-making.
- Prototyping is a catalyst for codifying and transferring tacit knowledge.
- Designers utilize opportunities of digital fabrication and DIY design repositories as well as manufacturing services.

We consider these findings exploratory, and while our research method and sample sizes does not allow for generalizations to the broader population of hardware start-ups, we have identified how certain prototyping focused practices exist. We find that this identification supports the motivation for this research project by verifying the importance of prototyping to designers in hardware start-ups.

While the focus of this thesis is not on product development projects in established organizations, it is still meaningful to reflect on whether the identified roles and purposes of prototypes can also be identified in different engineering contexts. In Draft IR a range of such cases are introduced and discussed. Below we provide a few examples:

- In three established companies - a consumer electronics company, a footwear company and a medical device company - Lauff et al. have identified a wide use of prototypes to support enhanced communication, increased learning, and informed decision-making (Carlye A. Lauff et al., 2018). These findings align well with Subrahmanian et al. who identified that prototypes can support communication and function as boundary objects in large organizations (2003).
- Gerber and Carroll identified that practitioners reframe failure as an opportunity for learning and supports a sense of forward progress when working with prototypes in a large technology firm (2012).
- From studying the automotive industry Erichsen et al. identified that prototypes

impacts knowledge acquisition and transfer (2016).
- Finally, through a study of eight diverse product development companies the term 'prototrialing' was introduced by Jensen et al., and is characterized by use of high-functional prototypes of low fidelity in early stage concept development. This with the objective to elicit 'unknown unknowns' (2017).

Collectively such findings outline that particular roles and purposes of prototypes can also be identified in different engineering contexts. It is however not clear to what extend they are generalizable, or in what development cultures, or particular product development contexts such dynamics are emphasized. In section 5.5 'Suggestions for Further Research' we encourage further work to study such dynamics.

**RQII: What main product development challenges for hardware start-ups can be identified?**

Our results for answering this second research questions draws primarily from paper B.

Through paper B, we studied teams of entrepreneurs working on consumer products, where funding had (at least partially) been obtained though reward based crowdfunding. The results of our analysis outline an overview of 20 different failure modes that were recorded for these development projects. We identified five challenges that were statistically significant in their occurrence for campaigns not meeting announced deadlines. Those we highlight as main product development challenges, and they are the following:

- The product is lacking preannounced and expected features.
- The product does not live up to expected levels of usability.
- The teams identify Design for Manufacturing deficiencies on the mature design.
- The team faces manufacturing quality issues, either from manufacturing processes not meeting expectations or a product design that is not suitable for selected manufacturing processes.
- The team faces management challenges related to their own organization and internal administration.

Also, it should not be left out, that the overall consequence of these challenges was delays in product launch, essentially underlining that delays should not be underestimated as a main product development challenge.

While other product development challenges could potentially also be identified through other research approaches, we find that the quantitative overview obtained through paper B, provides a valuable overview for supporting hardware start-ups in their design activities.

Finally, our answers to this research question build on the assumption that challenges to hardware start-ups that raise funds through crowdfunding are also representative to teams pursuing other funding schemes, which was also previously disused in Section 4.3.4.

**RQIII: How can hardware-start-ups make use of digital fabrication technologies in the prototyping of consumer products?**

To answer this open-ended question, we provide two studies that explore prototyping utilizing digital fabrication technologies. The studies are respectively paper D and paper E, which both focus at understanding the desirability of consumer products through feedback collected from potential users of the respective products in focus.

Through paper E we propose four design heuristics. One of these is to use low fidelity prototypes whenever suitable. This could seem obvious, but from our evaluation of best practice principles in paper F, we find that following this strategy of *building only the minimum model needed* is not obvious to designers. In fact, only two of ten design teams followed the strategy.

Building on the insight that low fidelity prototypes can be of high value, we conducted the study presented in paper E. The objective is to explore the opportunities in combining prototyping through digital fabrication and the data driven design approach, 'DoE'. The study introduces a seven-step process to apply this principle and a statistical model is developed. Through this model it is possible to identify the primary drivers of product desirability and also further to study the dynamics among the explored parameters e.g. by investigating their sensitivity and interactions. Such opportunities bring new insights for hardware start-ups, which are working towards their first product launch and only have very limited insights in market dynamics.

To summarize, the insights obtained through these two studies have lead us to the following conclusion for this research question:
For early stage development of consumer products, hardware start-ups should focus at using low fidelity prototypes when conducting user studies. This despite wide opportunities for utilizing digital fabrication technologies to fabricate advanced and high fidelity prototypes. Rather, we recommend that resources and potentials of digital fabrication are oriented towards the fabrication of many product configurations through prototypes of low fidelity. Such prototypes can be utilized for conducting data driven development activities with characteristics as the ones outlined in paper E.

However, as also recommended in paper D, small qualitative studies should though not be excluded from development activities and are of high value for theory building and initial insights.

Finally, as initially stated. This research question has an open ended formulation and our conclusions are drawn based on the limited studies conducted in this research project. In this light, the question should not be considered fully saturated.

**RQIV: How can designers with limited or intermediate product development experience be supported in their prototyping activities?**

Different strategies could be deployed to support novice designers in their prototyping activities. In this project we have proposed the prototyping framework the Prototyping Planner. The framework is introduced in paper F, which outlines respectively its conceptualization process and a controlled experiment to evaluate the framework.
In this section it is our aim to shed light on why we see the Prototyping Planner as 'a good' approach for supporting novice designers in their prototyping activities. First, we introduce how evidence on lacking prototyping competencies can be identified in literature. Second, we point to accumulated insights obtained through this project, and finally, we argue why a framework like the Prototyping Planner is a suitable type of support for accommodating the identified implications.

Through the literature review included in paper F, we introduce how novice designers in existing literature are documented to have underdeveloped competencies in three 'generic' aspects of product development, and also for five aspects that are of particular relevance to prototyping. Examples are to sub-prioritize problem scoping and information gathering (Atman et al., 2007) and to omit preliminary evaluations of their design decisions prior to direct implementation (Ahmed et al., 2003). A need for supporting prototyping competencies can hereby be identified in the existing literature.

Throughout this project a range of insights and concrete results further support the need for nurturing prototyping competencies among novice designers;

- The explorative study (IR) of hardware start-ups identified how all participating teams made active use of prototyping, and a sub-group of these in particular practices a prototype driven development culture. This underlining how the skillset to work effectively with prototypes is a valuable competence for engineers pursuing careers as hardware entrepreneurs.
- The quantitative study (paper B) of crowdfunding campaigns identified a set of main product development challenges for hardware start-ups. We are not able to present a causal relationship but still argue that these challenges could be mitigated by rigorously and proper prototyping earlier in the development process.
- In paper F, we present results based on the evaluating of build logs of novice design teams. These logs document that the design teams working without prototyping support – a year prior to the introduction of the Prototyping Planner - did not fully comprehend fundamental prototyping metrics, such as using appropriate types of prototypes to address specific design questions.

A need for supporting prototyping competencies was hereby identified through three of our research activities.

As initially stated, prototyping competencies can be nurtured through different strategies. In this paragraph we outline why a framework in the format of the Prototyping Planner was chosen; Through Paper C, we obtained a range of insights regarding the participants view on different types of design methodology and support. In summary we concluded that:

- Some entrepreneurs dislike the format of academic papers.
- That comprehensive process models are not suitable for the development activities in start-ups.
- Rather the teams prefer less comprehensive and ‘lightweight’ frameworks like the metrics described in *The Lean Startup* by (Ries, 2011) and the popular *Business Model Canvas* introduced by (Osterwalder and Pigneur, 2010).

Further, the research context for this project favored a support framework that could be communicated and conveyed to designers taking part in different activities, courses and programs offered at DTU Skylab. This preferably through an appealing format that allows for integration with other different overall development paradigms and contexts.

The insights presented above helped us clarify that the initial format of the Prototyping Planner where we draw on the four step Shewhart Cycle (as outlined in appended Paper F).

In paper F it is further presented how existing prototyping support does not cover the full prototyping cycle, and is narrow in focus. In contrast, the foundational metrics of the Prototyping Planner cover the full prototyping cycle through the four steps: Think, Build, Expose and Act. It is the ambition that this scope, covering the full prototyping cycle, helps novice designers adopt some of the identified design practices performed by experts. Examples are to spend more time in problem scoping and information gathering (Atman et al., 2007) and to make preliminary evaluations of their design decisions prior to implementation (Ahmed et al., 2003).

Alternative approaches for design support focused on prototyping could also be envisioned. Such could e.g. be in the format of a card deck or an interactive digital application. It was though hypothesized that the format of a card deck would be prone to lack of integrity and to highlight the need for focus on the full prototyping cycle. To develop an interactive application was initially discussed but was discarded due to lack of resources and agility throughout iterative development.

Hereby, we found that the Prototyping Planner was ‘a good’ answer to this research question on how designers with limited or intermediate product development experience be supported in their prototyping activities. Paradoxically, a need for knowledge sharing and general digitalization of work were though identified as improvement potentials of the existing layout of the Prototyping Planner. This is further outlined in paper F.

## 5.2 Impact and contributions of research

In the following section we discuss the contributions and impact of this project in academia and for practitioners, respectively.

### 5.2.1 Academic value and main contributions

This project was conducted within the topic of engineering design. In this section we highlight our main academic contributions in this research field. Our contributions are:

- Overview of how prototypes are defined in the engineering design literature.
- Exploratory research on product development in hardware start-ups, where insights can be of value for future theory building. Our insights are focused on:
  - The roles and purposes on of prototypes in hardware start-ups where we identify a development culture particularly focused at prototyping.
  - Design teams and their use and knowledge of existing design methodology. Here, we provide contemporary insights in current practices in hardware start-ups.

- Identification of the most commonly occurring product development challenges that hinder success of hardware start-ups (on crowdfunding platforms).

- Exploration of how hardware start-ups can utilize digital fabrication for prototyping of consumer products. We find that:
  - Despite wide opportunities for fabrication of advanced models, prototypes at low fidelity are of high value when conducting user studies.
  - The potentials of digital fabrication technologies can be harvested by combining low fidelity prototypes and data-driven design approaches e.g. DoE.

- Finally, we propose the Prototyping Planner. The conceptualization process and evaluation of this prototyping framework brings three contributions:
  - An overview of product development competencies central to prototyping, where the literature has identified design efforts of novice designers to be inferior.
  - Insights on five central aspects for a prototyping framework derived from a workshop with experienced practitioners.
  - Insights on the designers perceived effect of a prototyping framework. Such have not previously been in focus for evaluation of existing prototyping support.

### 5.2.2 Impact and value for practitioners

Overall, a range of events and talks have helped disseminate knowledge on the research conducted in this project. Participants generally represented people directly involved in prototyping activities, as well as those with educational responsibilities or working in different support functions.

A side effect of studying hardware start-ups through crowdfunding has been a collaboration with Kickstarter.com, who were interested in learning more about the performance and challenges of the start-ups making use of their platform. Such insights might result in concrete future actions for how to better support the users of the crowdfunding platform. Also, a booklet has been written on the topic of crowdfunding and is available for download at DTU Skylab’s website.

Two of the studies in this project were written in direct collaboration with start-up companies, who were interested in expanding their knowledge on prototyping. The study focused on applying DoE in prototyping was also co-authored in collaboration with a Mechanical Design Engineer from a Danish 'med-tech' company. The company were interested in insights into whether such a development approach could be feasible in their organization. Further evaluations are being conducted at present. The study has further been recognized by the SAS organization and invited for presentation at SAS JMP Discovery Summit, spring 2019 (SAS Institute Inc., 2018).

Regarding the Prototyping Planner, the team manager responsible for start-up support and prototyping workshops at DTU Skylab has expressed interest in supporting future development of the framework. This combines with ambitions of a general implementation in future coaching activities and support programs.
Further, the two prototyping workshop managers at DTU Skylab have also expressed interest in adapting the framework. They envision, that the framework could help support the dialogue between workshop users and support staff. Concretely, this dialogue is focused at determining what prototypes to build. A central aspect for successfully supporting the workshop users, is a shared understanding of what design questions to be investigated, and what type of prototyping activity the designer intends to conduct. This application of the framework was not originally intended but can be tested and evaluated in further work.

## 5.3 Research limitations

As with all research that builds on the researcher's interpretations, there are some limitations. First of all, there is a risk of personal biases and the possibility that perspectives or insights were left out by accident. Through this project we have strived to work systematically and use tools such as triangulation of data (Paper B), and interrater assessments (Paper F) to mediate such risks.

Part of this project builds on qualitative approaches, such as semi-structured interviews, through which we have worked to expand the existing theoretical understanding of prototyping activities. The nature of qualitative research makes it challenging to make generalizations based on these studies and should be acknowledged as a limitation for the more general validity of the research results. Essentially, all research projects where a sample of the general population is studied includes a risk of sample selection bias.

In this project the empirical foundation concerns young hardware start-ups (focusing on consumer products, without a previous product portfolio or extensive resources) which allows for a certain project focus. A limitation for this focus of the research is that potentially attractive prototyping approaches practiced the established industry are potentially not identified. This could e.g. be in the context of product development projects concerning new and novel products.

We have generally sought to reflect on, and highlight, aspects of our work, where such restrictions of our results exist and will further do so throughout section 5.4.

## 5.4 Evaluation of the research results

In the following section we evaluate our work. In order to reflect on the conducted research methods and the study objectives, we group our work in four groups for this process. The groups are illustrated and introduced in Figure 31. Here we further remind the reader of Figure 13, which illustrates the overall DRM layout for the research projects, including the relations among research questions, conducted studies and associated research methods.

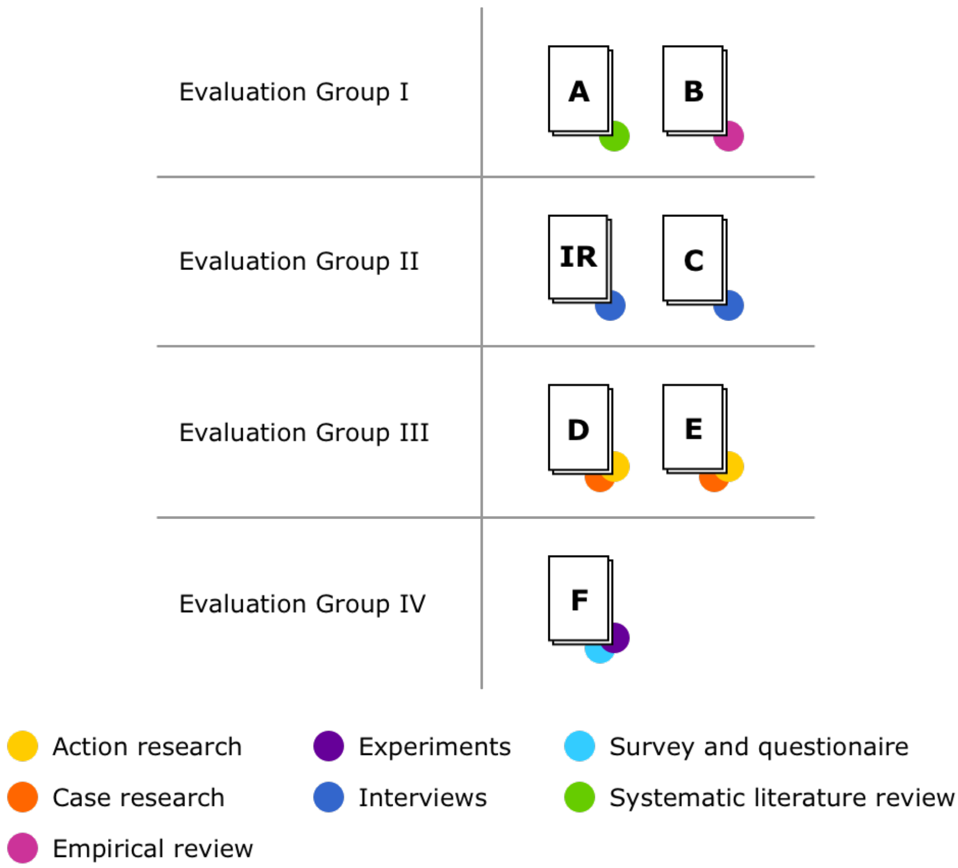



*Figure 31: Grouping of studies for evaluation.*

For Group I – Group III we will evaluate the validity, completeness and generality of the work. For Group IV we will apply the validation square by Pedersen et al. (2000), which was previously introduced in Section 2.3

### 5.4.1 Evaluation of studies Group I – Group III

In this section we evaluate the studies in Group I – Group III according to the following three criteria:

- Validity: *How was the result conceived?*
- Completeness: *How well do the results provide answer for the research questions*?

- Generality: *How can the results be used to generalize beyond the case examples*?

Validity:

- Group I: The papers in this group represent a systematic literature review and what could be categorized as an “empirical review” of Kickstarter.com. The literature review outlines the overall inclusion criteria for the study, and the reviewing process was systematically conducted. We hereby find that the results are valid under the conditions outlined in the paper. The review of Kickstarter.com also outlines specific inclusion criteria for the study and was systematically conducted, including a failure mode model. The validity of the study, however, has three limitations: i) A subset of the dataset was evaluated. ii) The data available to the authors have the potential to contain biased information. iii) Because of collaborative analysis, it was not possible to conduct an interrater reliability assessment. The authors used two approaches to mitigate such potential limitations of validity: First, the authors worked until a saturated understanding was established and overall statistical analysis was possible. Second, the authors triangulated different data sources to mitigate risks of bias and increase validity.

- Group II: The studies in this group are based on semi-structured interviews with nine and 13 hardware start-ups, respectively. To ensure a rigorous study, identical interview protocols was used for all interviews, and for both studies the correctness and accuracy of notes and directly coded results were verified by interviewees preceding the interviews. Furthermore, the interviews were audio recorded and subsequently coded by the authors. The results presented are hereby considered valid.

- Group III: The studies in this category were conducted in collaboration with two start-up companies. In both studies, user tests were conducted with a respective 44 and 66 participants within a defined target group. The user tests were conducted by drawing on previous studies (Acosta et al., 2008; Benedek and Miner, 2002; Deininger et al., 2017b; Alexander, 2000) and by using identical (pre-rehearsed) procedures and questions allowing for direct coding on Likert scales. Paper E includes further seven user studies to validate the statistical model established. In this light we find that the results outlined in both studies are valid.
  Both studies were conducted as a mixture of case research and action research as it was introduced in section 2.4.2. Concretely both start-ups were supported in the research design and data analysis but no direct engagement or interventions were made to the ongoing product development activities.

Completeness:

- Group I: The literature review in this category provides a concrete answer to the research question. However, data can always be arranged in different ways and different focuses could be applied. In this sense, the study is not exhaustive, and other aspects could be disclosed from different focuses in the analysis. The analysis of Kickstarter.com was conducted until saturation in understanding by the researchers, and a range of results are backed by statistical significance. The study provides sufficient answers to the research question, but different methods could disclose further or different main challenges for hardware start-ups.

- Group II: The studies based on interviews provide answers to the relevant research questions. The limited sample sizes provide some restrictions regarding generalizability of results, but the patterns identified sufficiently underline prototyping as a valuable design tool and exemplify the relevance of this project. We further find that related research projects have successfully used comparable sample sizes for studying prototyping practices (Jensen et al., 2017; Hess and Summers, 2013).

- Group III: The use of digital fabrication for prototyping is studied through collaboration with start-ups. The studies are exploratory and provide examples that feed into the research question of how start-ups can make use of digital fabrication for prototyping. Because of the open-ended formulation of the research question, we are not able to provide an exhaustive or complete answer. The studies do, however, cohere with a new research trend on ways to prototype in the *fuzzy front end* by leveraging emerging technologies (Jensen, 2017), and also serve as collective contributions to the current research gap identified by Camburn et al. and introduced in Section 1.1.2.

Generality:

- Group I: Our literature study is based on prototype definitions in the literature and cannot necessarily be generalized beyond the data corpus included in the study. If the results are also generalizable to industrial practice renders further investigation, but two of the five groups of prototype definitions were identified through our interviews with hardware start-ups. We find that the review of Kickstarter.com is fully generalizable to the reward-based crowdfunding domain that focuses on hardware development and practices the 'all or nothing principle.' We further assume that hardware start-ups that completed their crowdfunding campaigns are widely facing challenges comparable to those pursuing other funding schemes. This hypothesis warrants further investigation before full generalizability of the results can be claimed and was previously discussed in Section 4.3.4.

- Group II: For the interview-based studies, participating hardware start-ups and interviewees were identified through online searching. They encompassed a rather broad portfolio of products and geographical locations as well as experience of the teams. This finding supports the generalizability of these studies' results. We should, however, be careful regarding generalizations to the full start-up population as there is still a risk of exception fallacy.

- Group III: For both studies conducted in collaboration with start-up companies, the development teams articulated that: i) Study results were valuable for the particular development project and worth the effort invested in time and resources. ii) The process was rich in learnings, which could be applied also to future development activities. These discoveries support both the internal and external value of the studies conducted, and the teams in both cases presented the reflections that the results would generalize to other projects. We support that the results can be generalized to other consumer hardware projects, where the desirability can be studied through test users.

### 5.4.2 Evaluation of Prescriptive Studies

In this section we evaluate Group IV, consisting of Paper F, which introduces the Prototyping Planner. We do this through the six statements from the validation square which are segmented in the two overall categories effectiveness and efficiency.

**Effectiveness**

- Individual constructs: The individual constructs of the Prototyping Planner draw on four main sources of input: i) existing frameworks and studies of prototyping (as outlined in Paper F), ii) needs identified in literature for supporting novice designers in prototyping competencies (as outlined in Paper F), iii) identified main challenges for start-up companies (appended Paper B) and iv) a workshop with five practitioners. This workshop had two main purposes: first, to verify a proposal for an initial set of constructs to include in the Prototyping Planner, and second, to receive feedback on further constructs of relevance for the framework. In combination these actions support the establishment of individual constructs.

- Internal consistency: The internal consistency among the individual constructs was inspired by the Shewhart Cycle as described by Deming (1986)and transferred to the characteristics of a prototyping process. This four-step approach was verified as appropriate through the aforementioned workshop with practitioners and has also successfully been used for other support frameworks (Hostettler et al., 2017) as also outlined in Paper F.

- Appropriateness of example: The Prototyping Planner was evaluated in two examples. The first was through a short design exercise as part of the aforementioned workshop. The second was through an educational design challenge with a total of 30 design teams (195 students) distributed in three groups. The first 10 teams participated in a pre-study. Sample A, functioned as a control group with 10 teams and sample B was supported through the Prototyping Planner. The design challenge was intended to mimic a real-world development context but also lacked certain dimensions, such as "the real-world complexity" and project period. The educational context though has the benefit of a controllable environment where a measureable success criterion can be identified as discussed in Section 2.3.
  Evaluations of the Prototyping Planner were in the design challenge performed in two dimensions: i) the perceived effect of the framework among participants and ii) the extent of best practice prototyping principles (from literature) that could be identified in the design process of each team. As discussed in Section 1.2.1 the

number of entrepreneurs with limited experience is increasing, and therefore the participants are, despite their status as students, representative of the intended target group for the Prototyping Planner.

**Efficiency**

- Usefulness of outcome from example: The short design exercise conducted at the workshop with practitioners supported the general consistency of the Prototyping Planner and verified that the framework was applicable to real-world design problems.

- Usefulness linked to applied theory, method or tool: The experiment conducted in Paper F outlines that the Prototyping Planner helped to establish a "prototyping mindset" among the participants, and a significant increase in prototyping best practice was evaluated for the design projects. These observations were verified through an interrater reliability study. Potential improvements of the framework were also identified and are further outlined in Paper F.

- Usefulness beyond the example: At present, initial implementation of the framework has been conducted through a prototyping workshop in a seed stage accelerator program at DTU. Evaluations were on par with or better than the ones outlined in Paper F. Further refinement of the framework is intended before the conducting of further evaluations and before application of the framework is recommended.

## 5.5 Suggestions for Further Research

A PhD project is a time restricted project and not all identified gaps and ideas can be pursued. Fortunately, there seems to be a growing interest in prototyping research and it is our belief, that the design research community will succeed in progressing the current understanding of the topic.

The following section outlines a range of suggestions for further research that we have identified throughout this project.

### 5.5.1 Product development in hardware start-ups

Within this project we have interviewed a limited sample of hardware start-ups, in what can be considered as exploratory research. We have observed how a range of these start-ups have a highly prototyping focused development culture. Through interviews, we can only expand our understanding of the roles and purposes of prototypes to a certain extend. We encourage further studies of prototyping practice in hardware start-ups to be conducted. This could also include to further investigate how different development approaches might be regionally or industry dependent.

### 5.5.2 Product development in established companies and industries

The need for further prototyping studies is not limited to the context of hardware start-ups. In section 1.1.2 it was pointed out how the current body of literature does not provide a saturated understanding of how prototypes are utilized in industry. Hereby, prototyping in various other engineering contexts could be studied. Such studies could e.g. include investigations of how the role and purposes of prototypes might vary in novel new product development projects (e.g. with *fuzzy front end* characteristics) versus more incremental product development projects, where the solution principle being developed is more well established. Various other variables such as the company development history, existing product portfolio, composition of the development team and the experience of individual team members are also relevant parameters to include in such studies.

### 5.5.3 New approaches for prototyping

The tools that designers can utilize for prototyping are constantly evolving. In this project we conducted two studies where digital fabrication technologies were utilized. We find that there a wide opportunity for further research in how emerging technologies can be utilized in product development. Our colleagues at DTU Mechanical Engineering have recently documented how technologies such as injection molding can utilize modular mold-systems with additively manufactured inserts (Zhang et al., 2018). Such concepts make 'low volume and high mix' manufacturing a reality in a desktop format. In this context various prototyping approaches could be identified and draw inspiration from the software industry. This ranging from simple A/B testing to more comprehensive data analysis approaches (Beizer, 2003), which could be applied for testing of new hardware products.
New opportunities also exceed the concept of digital fabrication. In her recent dissertation Matilde B. Jensen suggested that new low cost sensor technologies could spark a new research topic on prototyping within different User Research areas (Jensen, 2017).

### 5.5.4 Further development of the Prototyping Planner

As previously stated, the Prototyping Planner is a work in progress framework, and a range of potentials for improvement has been identified. We intend to continue the development of the framework, and future opportunities also include validating the framework in an industrial context. Future evaluations of the Prototyping Planner (and prototyping frameworks in general) could further include how designer's preferences and working styles affect the perceived value of support.

# 6 Final Remarks

This thesis concludes my three year PhD project at DTU.
At times difficult and confusing but also a process of learning. Both from others and from my own mistakes, and from trying again.

In hindsight I look back at many good experiences and see that this project has also built on me as a person. During my time as an engineering student at DTU, we focused our efforts in solving problems by synthesizing domain knowledge and technical skills. We used design methods to navigate this process along with our creativity and empathy. Through this project I have seen myself as an apprentice working towards understanding and adapting the competencies to conduct research.
I will end this work with two quotes which helped build such understanding. This in the context of a good discussion among the participants at Summer School on Engineering Design Research in 2016, orchestrated by the three Professors Christian Weber, Lucienne Blessing and Mogens Myrup Andreasen illustrated in Figure 32. Discussion might be a researcher's most important tool. Thank you:

"*Knowledge is justified true belief"*
- Plato

*"For true belief to count as knowledge, it is necessary that they originate in sources we have a good reason to consider reliable"*
- Stanford encyclopedia of philosophy


*Figure 32: Drawing by Tomislav Martinic, PhD Student at University of Zagreb*

# References


3D Systems, Inc., 2018. 3dsystems. 3dsystems,com. URL https://www.3dsystems.com/ (accessed 10.26.18).

Abbas, A.E., Howard, R.A., 2015. Foundations of decision analysis. Pearson Higher Ed.

Acosta, O., Víquez, F., Cubero, E., 2008. Optimisation of low calorie mixed fruit jelly by response surface methodology. Food Qual. Prefer. 19, 79–85. https://doi.org/10.1016/j.foodqual.2007.06.010

Acs, Z., Szerb, L., Lioyd, A., 2018. Global Entrepreneurship Index.

Ahmed, S., Wallace, K.M., 2004. Identifying and supporting the knowledge needs of novice designers within the aerospace industry. J. Eng. Des. 15, 475–492. https://doi.org/10.1080/09544820410001708430

Ahmed, S., Wallace, K.M., Blessing, L.T., 2003. Understanding the differences between how novice and experienced designers approach design tasks. Res. Eng. Des. 14, 1–11.

Alexander, M.T., 2000. Response surface optimization using JMP® software.

Anderson, C., 2012. Makers : den nye industrielle revolution. Lindhardt og Ringhof.

Andreasen, M.M., 2011. 45 Years with design methodology. J. Eng. Des. 22, 293–332.

Andreasen, M.M., Hansen, C.T., Cash, P., 2015. Conceptual Design. Springer International Publishing, Cham.

Araujo, C.S., 2001. Acquisition of product development tools in industry: A theoretical contribution. Technical University of Denmark, DTU, Lyngby,.

Atman, C.J., Adams, R.S., Cardella, M.E., Turns, J., Mosborg, S., Saleem, J., 2007. Engineering Design Processes: A Comparison of Students and Expert Practitioners. J. Eng. Educ. 96, 359–379. https://doi.org/10.1002/j.2168-9830.2007.tb00945.x

Aulet, B., 2013. Disciplined entrepreneurship: 24 steps to a successful startup. John Wiley & Sons.

Beizer, B., 2003. Software testing techniques. Dreamtech Press.

Benedek, J., Miner, T., 2002. Measuring Desirability: New methods for evaluating desirability in a usability lab setting. Proc. Usability Prof. Assoc. 2003, 57.

Blank, S., 2012. The startup owner's manual: The step-by-step guide for building a great company. BookBaby.

Blessing, L.T.M., Chakrabarti, A., 2009. DRM, a design research methodology. Springer.

Blessing, L.T.M., Chakrabarti, A., Wallace, K.M., 1998. An overview of descriptive studies in relation to a general design research methodology, in: Designers. Springer, pp. 42–56.

Brown, T., 2009. Change by design. Harpercollins Publishers Inc.

Buur, J., 1990. A theoretical approach to mechatronics design, IK publication ; 90.74 A. Technical University of Denmark (DTU).

Buur, J., 1989. Design models in mechatronic product development. Des. Stud. 10, 155–162. https://doi.org/10.1016/0142-694x(89)90033-1

Camburn, B., 2015. A Systematic Method for Design Prototyping. J. Mech. Des. 137, 081102. https://doi.org/10.1115/1.4030331

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., Wood, K., 2017. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Des. Sci. 3, e13. https://doi.org/10.1017/dsj.2017.10

Camburn, B., Wood, K., 2018. Principles of maker and DIY fabrication: Enabling design prototypes at low cost. Des. Stud. https://doi.org/10.1016/j.destud.2018.04.002

Camburn, B.A., 2015. Design prototyping methods (PhD Dissertation). The University of Texas at Austin.

Camburn, B. A., Dunlap, B., Viswanathan, V., Linsey, J., Jensen, D.D., Crawford, R., Otto, K., Wood, K.L., 2013. Connecting Design Problem Characteristics to Prototyping Choices to Form a Prototyping Strategy, in: Proc. ASEE Annual Conference 2013.

Camburn, Bradley A., Dunlap, B.U., Kuhr, R., Viswanathan, V.K., Linsey, J.S., Jensen, D.D., Crawford, R.H., Otto, K., Wood, K.L., 2013. Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment, in: ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V005T06A033–V005T06A033.

Camburn, B.A., Jensen, D., Sng, K.H., Perez, K.B., Otto, K., Wood, K.L., Crawford, R., 2015. The Way Makers Prototype : Principles of DIY Design. Proc. ASME 2015 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf. 7, 1–10. https://doi.org/10.1115/DETC201546295

Carulli, M., Bordegoni, M., Cugini, U., 2013. An approach for capturing the voice of the customer based on virtual prototyping. J. Intell. Manuf. 24, 887–903.

Castellion, G., Markham, S.K., 2013. Perspective: New Product Failure Rates: Influence of *Argumentum ad Populum* and Self-Interest: New Product Failure Rates. J. Prod. Innov. Manag. 30, 976–979. https://doi.org/10.1111/j.1540-5885.2012.01009.x

Cavalcanti, G., 2013. Is it a Hackerspace, Makerspace, TechShop, or FabLab? [WWW Document]. Make DIY Proj. - Electron. Crafts Ideas Mak. URL http://makezine.com/2013/05/22/the-difference-between-hackerspaces-makerspaces-techshops-and-fablabs/ (accessed 2.15.16).

Chakrabarti, A., Lindemann, U., 2015. Impact of Design Research on Industrial Practice: Tools, Technology, and Training. Springer.

Checkland, P., Holwell, S., 2007. Action Research, in: Kock, N. (Ed.), Information Systems Action Research: An Applied View of Emerging Concepts and Methods, Integrated Series in Information Systems. Springer US, Boston, MA, pp. 3–17. https://doi.org/10.1007/978-0-387-36060-7_1

Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L., Crawford, R.H., 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables, in: American Society for Engineering Education. American Society for Engineering Education.

Compass, 2015. The Global Startup Ecosystem Ranking 2015. he Startup Ecosystem Report Series Compass.

Cooper, R.G., 2001. Winning at New Products, Accelerating the Process from Idea to Launch, 2001. Camb. Perseus.

Cross, N., 2008. Engineering design methods : strategies for product design. John Wiley & Sons.

Cross, N., 2007. Forty years of design research. Des. Stud. 28, 1–4. https://doi.org/10.1016/j.destud.2006.11.004
Cross, N., 2001. Designerly ways of knowing: Design discipline versus design science. Des. Issues 17, 49–55.
Daalhuizen, J., Badke-Schaub, P., 2011. The use of methods by advanced beginner and expert industrial designers in non-routine situations: a quasi-experiment. Int. J. Prod. Dev. 15, 54–70. https://doi.org/10.1504/IJPD.2011.043661
Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., 2017a. Novice designers' use of prototypes in engineering design. Des. Stud. 51, 25–65. https://doi.org/10.1016/j.destud.2017.04.002
Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., Obed, S., Effah Kaufmann, 2017b. Does prototype format influence stakeholder design input? Presented at the ICED 2017, Vancouver.
Deming, W.E., 1986. Out of the Crisis. Cambridge University Press.
Deon J. de Beer, Ludrick J. Barnard, Gerrie J. Booysen, 2004. Three-dimensional plotting as a visualisation aid for architectural use. Rapid Prototyp. J. 10, 146–151. https://doi.org/10.1108/13552540410527015
Dow, S.P., Glassco, A., Kass, J., Schwarz, M., Klemmer, S.R., 2009. The effect of parallel prototyping on design performance, learning, and self-efficacy, in: Stanford Tech Report.
Dragon Innovation, 2016. . Dragon Innov. Blog.
Eckert, C.M., Clarkson, P.J., Stacey, M.K., 2003. THE SPIRAL OF APPLIED RESEARCH: A METHODOLOGICAL VIEW ON INTEGRATED DESIGN RESEARCH, in: ICED 03 STOCKHOLM, AUGUST 19-21, 2003. Presented at the INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, p. 10.
Einstein, B., 2015. The Illustrated Guide to Product Development (Part 1: Ideation). Bolt Blog. URL https://blog.bolt.io/the-illustrated-guide-to-product-development-part-1-ideation-ab797df1dac7#.harn8xqx4 (accessed 11.22.16).
Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manage. Rev. 14, 532–550.
Elverum, C.W., Welo, T., 2014. The Role of Early Prototypes in Concept Development: Insights from the Automotive Industry. Procedia CIRP, 24th CIRP Design Conference 21, 491–496. https://doi.org/10.1016/j.procir.2014.03.127
Elverum, C.W., Welo, T., Steinert, M., 2014. The Fuzzy Front End: Concept Development in the Automotive Industry V007T07A037. https://doi.org/10.1115/DETC2014-35138
Erichsen, J.A.B., Steinert, M., Pedersen, A.L., Welo, T., 2016. Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry. 2016 Annu. Ieee Syst. Conf. Syscon 485–490.
Gerber, E., Carroll, M., 2012. The psychological experience of prototyping. Des. Stud. 33, 64–84. https://doi.org/10.1016/j.destud.2011.06.005
Hannah, R., Michaelraj, A., Summers, J.D., 2008. A Proposed Taxonomy for Physical Prototypes: Structure and Validation, in: ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. 231–243.
Hempler, V., 2018. DTU's strategy 2014-2019 - DTU. https://www.dtu.dk. URL https://www.dtu.dk/english/about/organization/strategy (accessed 10.20.18).

Hess, T., Summers, J.D., 2013. CASE STUDY: EVIDENCE OF PROTOTYPING ROLES IN CONCEPTUAL DESIGN. Presented at the ICED.
Horváth, I., 2007. COMPARISON OF THREE METHODOLOGICAL APPROACHES OF DESIGN RESEARCH, in: ICED 07 28 - 31 AUGUST 2007. Presented at the INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07, CITÉ DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE, p. 11.
Hostettler, R., Böhmer, A., lindemann, udo, knoll, alois, 2017. TAF Agile Framework.
Houde, S., Hill, C., 1997. What do prototypes prototype. Handb. Hum.-Comput. Interact. 2, 367–381.
Iman, J., 2018. Tech in Asia - Connecting Asia's startup ecosystem. Tech Asia. URL https://www.techinasia.com (accessed 10.13.18).
IRIS Group, 2018. [Entrepreneurship at DTU for two decades] -Iværksætteri-på-DTU-gennem-to-årtier-indsats,resultater og-samfundsøkonomiske effekter (Consultancy report). IRIS Group.
Jang, J., Schunn, C.D., 2012. Physical design tools support and hinder innovative engineering design. J. Mech. Des. 134, 041001.
Janson, M.A., Smith, L.D., 1985. Prototyping for systems development: a critical appraisal. Mis Q. 305–316.
Jensen, L.S., Özkil, A.G., Mougaard, K., 2016. Makerspaces in Engineering Education: A Case Study. Proc. Asme Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf. Vol 3.
Jensen, M.B., 2017. Opportunities of Industry-Based Makerspaces - New Ways of Prototyping in the Fuzzy Front End (PhD Thesis). Norwegian University of Science and Technology, NTNU.
Jensen, M.B., Elverum, C.W., Steinert, M., 2017. Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. Des. Stud. 49, 1–31. https://doi.org/10.1016/j.destud.2016.12.002
Jørgensen, K., 1992. Videnskabelige arbejdsparadigmer [Scientific work paradigms]: Inst. Prod. Aalb. Univ. Den.
Kelley, T., 2010. Prototyping is the shorthand of innovation. Des. Manag. J. Former Ser. 12, 35–42. https://doi.org/10.1111/j.1948-7169.2001.tb00551.x
Kershaw, T., Holtta-Otto, K., Lee, Y.S., 2011. The effect of prototyping and critical feedback on fixation in engineering design, in: Proceedings of the Annual Meeting of the Cognitive Science Society.
Kirjavainen, A., Nousiainen, T., Kankaanranta, M., 2005. Prototyping in Educational Game Design, in: CHI. pp. 24–27.
Lauff, C., Kotys-Schwartz, D., Rentschler, M.E., 2017. Perceptions of Prototypes: Pilot Study Comparing Students and Professionals. ASME, p. V003T04A011. https://doi.org/10.1115/DETC2017-68117
Lauff, Carlye A., Kotys-Schwartz, D., Rentschler, M.E., 2018. What is a Prototype? What are the Roles of Prototypes in Companies? J. Mech. Des. 140, 061102. https://doi.org/10.1115/1.4039340
Lauff, Carlye A, Kotys-Schwartz, D., Rentschler, M.E., 2018. Prototyping Canvas: Building Purposeful Prototypes During Early Stage Design, in: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE 2018. Presented at the IDETC/CIE 2018, Quebec City, Canada, p. 3.

Leifer, L.J., Steinert, M., 2014. Dancing with Ambiguity: Causality Behavior, Design Thinking, and Triple-Loop-Learning, in: Gassmann, O., Schweitzer, F. (Eds.), Management of the Fuzzy Front End of Innovation. Springer International Publishing, pp. 141–158. https://doi.org/10.1007/978-3-319-01056-4_11

Lim, Y.-K., Stolterman, E., Tenenberg, J., 2008. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Trans. Comput.-Hum. Interact. TOCHI 15, 7.

Lipson, H., Kurman, M., 2013. Fabricated: The new world of 3D printing. John Wiley & Sons.

Maier, A.M., Wynn, D.C., Howard, T.J., Andreasen, M.M., 2014. Perceiving Design as Modelling: A Cybernetic Systems Perspective, in: Chakrabarti, A., Blessing, L.T.M. (Eds.), An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations. Springer London, London, pp. 133–149. https://doi.org/10.1007/978-1-4471-6338-1_7

McMahon, C.A., 2012. Reflections on diversity in design research. J. Eng. Des. 23, 563–576. https://doi.org/10.1080/09544828.2012.676634

Menold, J., Jablokow, K., Simpson, T., 2017. Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. Des. Stud. 50, 70–112.

Menold, J., Simpson, T.W., Jablokow, K., 2018. The prototype for X framework: exploring the effects of a structured prototyping framework on functional prototypes. Res. Eng. Des. 1–15. https://doi.org/10.1007/s00163-018-0289-4

Menold, J.D., 2017. Prototype For X (PFX): A Prototyping Framework to Support Product Design (PhD Dissertation). The Pennsylvania State University.

Moe, R.E., Jensen, D.D., Wood, K.L., 2004. Prototype partitioning based on requirement flexibility, in: Proc. ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2004.

Neeley, W.L., Lim, K., Zhu, A., Yang, M.C., 2013. Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design. ASME Pap. No DETC2013-12635.

Osterwalder, A., Pigneur, Y., 2010. Business model generation: a handbook for visionaries, game changers, and challengers. John Wiley & Sons.

Otto, K.N., Wood, K.L., 2003. Product design: techniques in reverse engineering and new product development. Prentice-Hall.

Ovesen, N., 2012. The challenges of becoming agile: Implementing and conducting scrum in integrated product development (PhD Thesis). Department of Architecture and Design, Aalborg University.

Özkil, A.G., 2017. Collective design in 3D printing: A large scale empirical study of designs, designers and evolution. Des. Stud. 51, 66–89. https://doi.org/10.1016/j.destud.2017.04.004

Pahl, G., Wallace, K., Blessing, L., Pahl, G. (Eds.), 2007. Engineering design: a systematic approach, 3rd ed. ed. Springer, London.

Papalambros, P.Y., 2015. Design Science: Why, What and How. Des. Sci. 1. https://doi.org/10.1017/dsj.2015.1

Pape Thomsen, R., 2018. DTU Skylab Annual Report 2017. http://www.skylab.dtu.dk. URL http://www.skylab.dtu.dk/about_us/press (accessed 10.22.18).

Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J.K., Mistree, F., 2000. Validating design methods and research: the validation square, in: ASME Design Engineering Technical Conferences. pp. 1–12.

Pei, E., Campbell, I., Evans, M., 2011. A Taxonomic Classification of Visual Design Representations Used by Industrial Designers and Engineering Designers. Des. J. 14, 64–91. https://doi.org/10.2752/175630610X12877385838803

Person, O., Daalhuizen, J., Gattol, V., 2012. Forming a Mindset: Design Students' Preconceptions about the Usefulness of Systematic Methods, in: DS 74: Proceedings of the 14th International Conference on Engineering & Product Design Education (E&PDE12) Design Education for Future Wellbeing, Antwerp, Belguim, 06-07.9.2012.

Pessant, J.R., McMahon, B.J., 1979. Participant observation of a major design decision in industry. Des. Stud. 1, 21–26.

Piper, R.J., 2013. How to write a systematic literature review.

Punkka, T., 2012. Agile Hardware and Co-Design, in: Embedded Systems Conference 2012, Boston,. Boston, MA, USA, p. 8.

Ries, E., 2011. The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses. Random House LLC.

Rothenberg, J., 1991. PROTOTYPING AS MODELING: WHAT IS BEING MODELED?, in: Dynamic Modelling of Information Systems. Elsevier, pp. 335–359. https://doi.org/10.1016/B978-0-444-88923-2.50018-5

SAS Institute Inc., 2018. Discovery Summit. URL https://discoverysummit.jmp/en/home.html (accessed 10.24.18).

Schmidt, T., Wallisch, A., Böhmer, A., Paetzold, K., Lindemann, U., 2017. Media Richness Theory in Agile Development: Choosing Appropriate Kinds of Prototypes to Obtain Reliable Feedback.

Schmidt, T.S., Weiss, S., Paetzold, K., 2018a. EXPECTED VS. REAL EFFECTS OF AGILE DEVELOPMENT OF PHYSICAL PRODUCTS: APPORTIONING THE HYPE, in: DS92: Proceedings of the DESIGN 2018 15th International Design Conference. pp. 2121–2132.

Schmidt, T.S., Weiss, S., Paetzold, K., Institut für Technische Produktentwicklung, 2018b. Agile Development of Physical Products: an Empirical Study about Motivations, Potentials and Applicability.

Simon, H.A., 1996. The sciences of the artificial. MIT press.

Stock, T., Seliger, G., 2016. Methodology for the Development of Hardware Startups. Adv. Mater. Res. 1140, 505–512. https://doi.org/10.4028/www.scientific.net/AMR.1140.505

Stratasys Ltd, 2018. Stratasysl3D. Strat. Print. Addit. Manuf. Strat. URL http://www.stratasys.com/ (accessed 10.26.18).

Subrahmanian, E., Monarch, I., Konda, S., Granger, H., Milliken, R., Westerberg, A., Group, T., 2003. Boundary Objects and Prototypes at the Interfaces of Engineering Design. Comput. Support. Coop. Work CSCW 12, 185–203. https://doi.org/10.1023/A:1023976111188

Sutton, S.M., 2000. The role of process in software start-up. IEEE Softw. 17, 33–39.

Takeuchi, H., Nonaka, I., 1986. New New Product Development Game. URL https://hbr.org/product/new-new-product-development-game/86116-PDF-ENG (accessed 11.28.17).
Thomke, S., Bell, D.E., 2001. Sequential testing in product development. Manag. Sci. 47, 308–323.
Thomke, S.H., 1998. Managing Experimentation in the Design of New Products. Manag. Sci. 44, 743–762. https://doi.org/10.1287/mnsc.44.6.743
Thornton, A.C., 2016. Why Is Manufacturing Difficult? by Dragon Innovation.
Troxler, P., Wolf, P., 2010. Bending the Rules. The Fab Lab Innovation Ecology, in: 11th International CINet Conference, Zurich, Switzerland. pp. 5–7.
Ullman, D.G., 2010. The mechanical design process, 4th ed. ed, McGraw-Hill series in mechanical engineering. McGraw-Hill Higher Education, Boston.
Ulrich, Eppinger, 2007. Product design and development. McGraw-Hill Higher Education.
Van Boeijen, A., Daalhuizen, J., van der Schoor, R., Zijlstra, J., 2014. Delft design guide: Design strategies and methods.
VDI-Fachbereich Produktentwicklung und Mechatronik: VDI 2206 – Entwicklungsmethodik für mechatronische Systeme, 2004. . VDI-Fachbereich.
Vetterli, C., Hoffmann, F., Brenner, W., Eppler, M.J., Uebernickel, F., 2012. Designing innovation: Prototypes and team performance in design thinking, in: ISPIM Conference Proceedings. The International Society for Professional Innovation Management (ISPIM), p. 1.
Viswanathan, V., 2014. A study on the role of physical models in the mitigation of design fixation. J. Eng. Des. 25, 25–43. https://doi.org/10.1080/09544828.2014.885934
Viswanathan, V., Linsey, J.S., 2012. Build to learn: effective strategies to train tomorrow's designers. age 25, 1.
Viswanathan, V.K., Linsey, J.S., 2013. Role of sunk cost in engineering idea generation: an experimental investigation. J. Mech. Des. 135, 121002.
Viswanathan, V.K., Linsey, J.S., 2012. Physical models and design thinking: A study of functionality, novelty and variety of ideas. J. Mech. Des. 134, 091004.
Wall, M.B., Ulrich, K.T., Flowers, W.C., 1992. Evaluating prototyping technologies for product design. Res. Eng. Des. 3, 163–177.
Wu, J.J., Atkinson, R.D., 2017. How Technology-Based Start-Ups Support U.S. Economic Growth. SSRN Electron. J. https://doi.org/10.2139/ssrn.3079624
Yang, M.C., 2005. A study of prototypes, design activity, and design outcome. Des. Stud. 26, 649–669.
Yin, R.K., 2009. Case Study Research: Design and Methods. SAGE.
Zhang, S.X., Cueto, J., 2017. The Study of Bias in Entrepreneurship. Entrep. Theory Pract. 41, 419–454. https://doi.org/10.1111/etap.12212
Zhang, Y., Pedersen, D.B., Mischkot, M., Calaon, M., Baruffi, F., Tosello, G., 2018. A Soft Tooling Process Chain for Injection Molding of a 3D Component with Micro Pillars. J. Vis. Exp. 138. https://doi.org/10.3791/57335

# Appended Papers

**Paper A**
**Prototypes in engineering design: Definitions and strategies**
Jensen, L.S., Özkil, A.G., Mortensen, N.H., (2016). In: DESIGN 2016 14th International Design Conference.

**Draft IR**
**A study of the roles and purposes of prototypes in 13 hardware start-ups**
Jensen, L.S., Özkil, A.G., (2018). Not submitted for publication

**Paper B**
**Identifying Challenges in Crowdfunded Product Development: A review of Kickstarter Projects**
Jensen, L.S., Özkil, A.G., (2018). In: Design Science Journal

**Paper C**
**Crowdfunded Product Development: A study of hardware start-ups**
Jensen, L.S., Özkil, A.G., (2017). In: Undergoing peer review for journal publication

**Paper D**
**PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT**
Jensen, L.S., Nissen, L., Bilde, N., Özkil, A.G., (2018). In: DESIGN 2018 15th International Design Conference.

**Paper E**
**PROTOTYPING FOR DESIRABILITY BY DESIGN OF EXPERIMENTS: A CASE STUDY OF A HARDWARE START-UP**
Jensen, L.S., Vorting, D., Villadsen, A., Mølleskov, L.H., Özkil, A.G., (2018). In: ASME 2018 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.

**Paper F**
**Fostering Prototyping mindsets: Towards the framework Prototyping Planner**
Jensen, L.S., Özkil, A.G., (2018). In: Submitted for peer review for journal publication

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

# PROTOTYPES IN ENGINEERING DESIGN: DEFINITIONS AND STRATEGIES

L. S. Jensen, A. G. Özkil and N. H. Mortensen

*Keywords: prototype definition, product development, prototyping strategy*

## 1. Introduction

Prototypes are essential in product development. They can help to create, explore, describe, test and analyse the item being designed. The role and the importance of prototyping has been rapidly changing and progressing as emerging business models - such as crowdfunding and new digital fabrication technologies - directly influence engineering design and product development practices.
Although they are an essential part of product development, the terms 'prototype' and 'prototyping' do not have commonly accepted definitions and refer to a range of artefacts and processes that have different meanings, purposes, and characteristics. This fragmentation stems from different industries and research fields, and we believe that there is a need for identifying and understanding the variations in definitions and strategic roles of prototypes in product development. This paper answers the following questions:

- How are 'prototypes' defined in engineering design literature?
- What are the strategic elements of prototyping?

The basis of this study is a systematic literature review of prototypes in engineering design and product development. The Scopus database was used to perform the review. We found that "prototype" is a very commonly used term in the literature (455,357 publications); whereas its combinations with search terms of 'engineering design' and 'product development' yield only 3,013 publications. The search results were manually screened for their relevance to the aims of this paper, and 81 publications that discuss prototypes and prototyping were identified. The references in these publications were also screened and added to the collection, resulting in 271 publications. This corpus included books, proceedings and journal publications, and constituted the basis of the work presented in this paper.
In the following section, we discuss types and purposes of prototypes and present 19 different definitions of the term that were found in the literature. There seems to be no overarching definition of a prototype, but we have identified five categories of prototype, based on their use and the research context in which they were defined. The third section focuses on the strategic role of prototypes in product development processes and discusses their relevance in terms of scale, integration, logistics, embodiment and evaluation. This leads to a discussion (Section 4), that deals with the increasing complexity and fragmentation of the terminology related to prototypes. We believe that recent advances in prototyping technologies and the use of prototypes in a wider range of activities within product development processes are not well-described in engineering design research. We therefore conclude that a more holistic overview of prototypes and new support tools for selecting prototyping technologies can help practitioners to apply the appropriate prototyping strategies at different stages of their product development.

## 2. Prototypes and prototyping in engineering design

Prototype and prototyping are two terms often used in the same context. Despite the lack of a general definition it is often accepted that the term *Prototype* designates a representative form of an idea whereas p*rototyping* is referred to as the activity of making and utilizing prototypes in design. [Lim et al. 2008]. When reviewing product development literature, it is clear that the term "prototype" is being used in a broad range of different ways. According to [Ravn et al. 2015] there are two main uses of the term prototype. Both of these serve the overall purpose of creating insights on the future product or object. The difference between the two usages is in terms of the 'width' of the reference and more specifically in what phases of the product development process prototypes are utilized.

The first usage includes a prototyping terminology that covers the whole product development process. Here every model representing a product or idea can be referred to as a prototype. Examples of this approach are found in e.g. [Houde and Hill 1997], [Ulrich and Eppinger 2007] and [Ullman 2010].

The second usage is more specific as it specifically applies the term prototype to a mature model of the product 'late' in the product development process. This model - or prototype – has evaluation as its primary objective [Buur and Andreasen 1989]. Other representations of product properties within this understanding are referred to as design models, design mock-ups or functional models and not prototypes. In this review we focus on these two uses of the term prototype.

### 2.1 Types and purposes of prototypes

Prototypes in different industries and research traditions serve different purposes: Industrial designers produce prototypes of conceptual ideas to explore form and geometry, engineers prototype designs to validate a functional principle or to benchmark performance and software developers write prototype programs to test user experience or requirement specifications.

A concrete representation and distinction of different types of prototypes is proposed by [Ulrich and Eppinger 2007]. They suggest that prototypes can be classified along two dimensions that relates to the nature of the prototype. The first is to what extend the prototype is physical as opposed to analytical. The second dimension is the degree to which a prototype is comprehensive as opposed to focused. This approach to illustrating different types of prototypes seems a strong tool for e.g. teaching or management related activities. One limitation is its lack of articulation about the actual purpose of the prototype. These authors did present four possible purposes of prototypes in product development:

- "Learning": is used to answer the type of questions "Will it work?" or "How well does it meet customers' needs?"
- "Communication": Prototyping enriches communication with various stakeholders such as management, vendors, partners, extended team members, customers and investors.
- "Integration": Prototypes can be used to ensure that components and subsystems of the product work together as expected.
- "Milestones": Particularly in the later stages of product development, prototypes are used to demonstrate that the product has achieved a desired level of functionality.

Authors such as [Polydoras et al. 2011], [Beaudouin-Lafon and Mackay 2003] and [Ullman 2010] present a relatively similar and compact classification of prototypes. The basis of these classifications are the prototype purposes, and [Ullman 2010], for example, also links the purpose to a specific state of the design process by defining prototype types such as a 'proof of concept prototype.' A dimension which is not addressed in these classifications is the fundamental purpose of a prototype. A prototype can be either a creative 'idea-generating tool' or a 'concluding tool'. This differentiation leads [Lindow and Sternitzke 2016] to two overall categories of prototype: 'The design prototype' and 'The technological prototype'. Similarly, [Lim et al. 2008] underline the differences between 'Prototypes as manifestations' and 'Prototypes as filters'. Based on the distinction between the terms and classifications, we argue that prototypes can serve respectively divergent (ideation, synthesis) and convergent (evaluation, selection) purposes in a product development process.

Another aspect is how well a prototype is capable of articulating something about its specific purpose. Every prototype is intended to have some characteristics in common with the future product or object being designed. These 'common characteristics' are the properties which can communicate something about the future product [Andreasen et al. 2015]. [Houde and Hill 1997] use the same argument and state that “Choosing the right kind of more focused prototype to build is an art in itself, and communicating its limited purposes to its various audiences is a critical aspect of its use.” One reason for this difficulty is that there is not necessarily a coherence between the label of the optimal prototype and the maturity level of the design – which is in conflict with the specific purpose classification by [Ullman 2010] of successive design stages. The challenge of creating the optimal prototype can only increase in complexity with ‘Concurrent Engineering’ for low cost, early market entry and an ever-increasing number of available tools for prototyping. [Houde and Hill 1997] propose a triangular model to describe what design questions to answer with the prototype, claiming that such an approach makes it easier to decide what kind of prototype to build. The triangular model describes the following four dimensions: 1: “Role” refers to the way in which it is useful to the user. 2: “Look and feel”: denotes questions about the sensory experience. 3: “Implementation”: refers to questions about the “nuts and bolts” of how it actually works. 4: “Integration”: Prototypes built to represent the complete user experience of an artefact. Such prototypes bring together the artefact’s intended design in terms of role, look and feel, and implementation. This is a valuable approach to the creation of prototypes but the concept does not follow ‘the train of thought’ to its logical conclusion, as it offers no elaborated and concrete support as a strategy or method for the actual prototyping approach.

### 2.2 Definitions of a prototype in the literature

From our literature review we present an overview of 19 definitions of the term ‘prototype’. The definitions have been collected from the publications where the term is expressed in relation to engineering design and product development. The results are shown in Table 1.

**Table 1. ‘Prototype’ definitions in engineering research**

| Author(s) and Publication | Definitions of prototype in Engineering |
|---|---|
| [Goldfarb and Kondratova 2004] - Proceedings of 7th CATE | “A prototype can be defined as a concrete representation of part or all of an interactive system.” |
| [Preece et al. 2015] - Book, John Wiley and Sons | “A prototype is one manifestation of a design that allows stakeholders to interact with it and to explore its suitability: It is limited in that a prototype will usually emphasize one set of product characteristics and de-emphasize others.” |
| [Jangir et al. 2012] - International Journal of Software Engineering and Applications | “A rudimentary sample, model, exemplar or archetype built to test so that the design can be changed if necessary before the product is manufactured commercially or can be said to be a concept or process or to act as a thing to be replicated or learned from.” |
| [de Beer et al. 2004] - Rapid prototyping journal + [Polydoras et al. 2011] - ISRN Mechanical Engineering | ”A prototype can be defined as an artefact incorporating characteristics of the new product under development that enables designers to test various aspects of their ideas before committing themselves to the expense and risks of producing commercial quantities.” |
| [Hannah et al. 2008] - ASME 2008 IDETC | “A prototype is a physical instantiation of a product meant to be used to help resolve one or more issues during product development.” |
| [Ulrich and Eppinger 2007] - Book, McGraw-Hill Higher Education | “An approximation of the product along one or more dimensions of interest.” |
| [Wall 1991] - Research in Engineering Design | “Prototypes are considered to be test beds that enable designers to test their design hypotheses.” |
| [Otto and Wood 2003] - Book, Pearson, Prentice Hall | ”An artefact or model of design which acts as a catalyst for further development and evolution.” |
| [Jensen et al. 2015] - Proceedings of 20th ICED | ”We understand ‘prototypes as a tool to learn.” |
| [Christie et al. 2012] - American Society for Engineering Education | ”An initial instantiation of a concept as part of the product development process.” |

| | |
|---|---|
| [Lindow and Sternitzke 2016] - Book, Springer | ”A material or virtual object, or an experimental arrangement, simple or more complex functionality in which an idea to be realised is manifested in different stages of development—in part only in its selected properties and components.” |
| [Drezner 1992] - National Defence Research Institute | ”A prototype is a distinct product (hardware or software) that allows hands-on testing in a realistic environment. In scope and scale, it represents a concept, subsystem, or production article with potential utility. It is built to improve the quality of decisions, not merely to demonstrate satisfaction of contract specifications. It is fabricated in the expectation of change, and is oriented towards providing information affecting risk management decisions. |
| [Wall 1991] - Research in Engineering Design | “Technically, a prototype is the first thing of its kind … In our definition of a prototype we include both electronic and physical representations of the part or product.” |
| [Yang 2005] - Design Studies | “A prototype is an early embodiment of a design concept. Prototypes can range from simple 2-D sketches that represent design thinking … to foam core mock-ups to sophisticated 3-D rapid prototyping designs that are nearly indistinguishable from a manufactured item. By definition, prototypes are not production stage design.” |
| [van Harmelen 1989] - proceedings of 5th BCSHCI | ”A prototype can be defined as a trial version of a software or hardware system.” |
| [Kirjavainen et al. 2005] - CHI2006 Conference | “A preliminary version or model of all or a part of a system before full commitment is made to develop it.” |
| [Krogstie 2012] - Book, Springer | "An executable model of (or parts of) an information system, which emphasises specific aspects of that system." |
| [Beaudouin-Lafon and Mackay 2003] - Human Computer Interaction | “We define a prototype as a concrete representation of part or all of an interactive system. A prototype is a tangible artefact, not an abstract description that requires interpretation.” |
| [Houde and Hill 1997] -Book, Elsevier | “We define a prototype as any representation of a design idea—regardless of medium.” |

Based on the definitions, we identified five prepositions that could categorize these definitions. In order to clarify their relation to specific stages of product development and illustrate overlapping elements in the definitions we have arranged them in an illustration, shown in Figure 1.

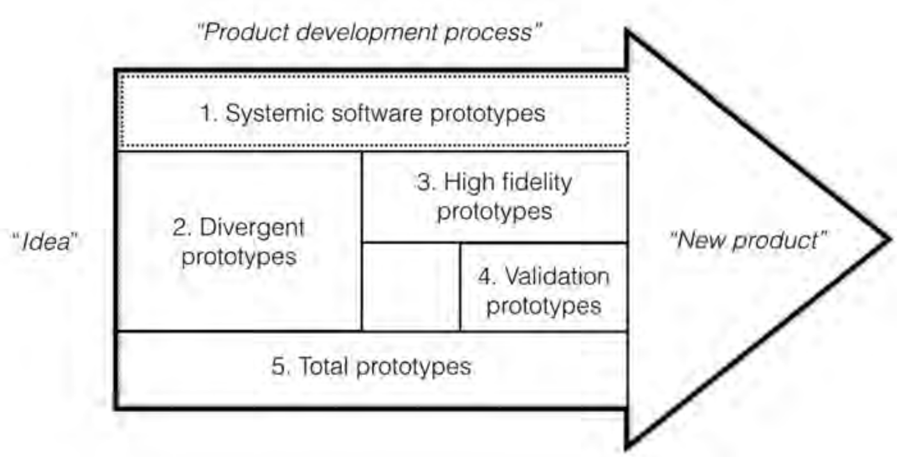



**Figure 1. Graphical illustration of five prepositions to categorise prototype definitions**

- Group 1: "Systemic Software Prototypes": These definitions originate from software engineering related publications. They represent systemic thinking and emphasize that prototyping activities with both partial and whole systems can take place. Such openness in scope and design stage relation is illustrated by the dotted enclosure in Figure 1. We see [Beaudouin-Lafon and Mackay 2003], [Goldfarb and Kondratova 2004] and [Krogstie 2012] as representatives of this group.
- Group 2: "Divergent Prototypes": Only [Jensen et al. 2015] and [Otto and Wood 2003], present definitions that includes a clearly divergent interpretation of prototypes. These two conclude this group and is opposed to the majority of definitions, which are oriented towards prototypes as convergent tools with a concluding nature. As the exploratory elements of product development are often concerned with the early design stages we link this group to the initial stages of the development process.
- Group 3: "High fidelity prototypes": These definitions generally imply that a prototype is concerned with some aspect of testing. [Beaudouin-Lafon and Mackay 2003] and [Drezner 1992] have presented definitions that also imply a prototype to include a certain level of complexity and maturity. We categorise these to generally relate to the later stages of product development.
- Group 4: "Validation prototypes": This group define a prototype as a mature model of a product before commitment to production is made. This is in line with narrow understanding of prototypes presented by [Buur 1989], which was introduced earlier. We recognise this understanding in [Kirjavainen et al. 2005] and [de Beer et al. 2004].
- Group 5: "Total prototypes": This group concerns an understanding where every model representing a product or idea can be referred to as a prototype. [Yang 2005] represents this "wide usage" of prototyping and specifically states that prototypes can be used at all stages of the design process.

## 3. Prototyping strategies

Prototyping strategies refer to the use of prototypes within product development, and also the concrete management of the design knowledge so generated. Our review reveals that little research has been concerned with strategies- Examples are [Camburn et al. 2013] and [Christie et al. 2012], where the authors proposed some initial steps towards a structured approach to organising prototyping efforts. On the other hand, a number of authors expressed the need for a better understanding of the role of prototypes and prototyping strategies in product development [Hardgrave et al. 1999], [Thomke 2003]. [Christie et al. 2012] suggested that a prototyping strategy can be defined as "The set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)." This would answer questions such as: "How many concepts should be prototyped?", "How many iterations of a concept should be built?", "Should the prototype be virtual or physical?", "Should subsystems be isolated?", "Should the prototype be scaled?" and "Should the design requirements be temporarily relaxed?" [Dunlap 2014].
We based our review of prototyping strategies on the model presented by [Camburn et al. 2013], and categorized the findings from the literature on strategic elements of prototyping in five sections: Scale, Integration, Logistics, Embodiment and Evaluation.

### 3.1 Scale

'High fidelity prototypes' vs. 'Low fidelity prototypes': What prototype fidelity suits your need? (Liu and Khooshabeh 2003) concluded that paper prototyping is insufficient for unique 'Ubiquitous computing' requirements. On the other hand [Youmans 2011] showed that 'low fidelity prototyping' can be a valuable tool in reducing design fixation.
'Full Size model' vs. 'Scaled model': For larger products scale models can be valuable, if it is not possible to produce a full size prototype quickly and easily. Examples could include models of buildings or ships [Christie et al. 2012].

### 3.2 Integration

'Sub-System' vs. 'Entire System': [Avrahami and Hudson 2002] argued that for interactive physical products it is important to holistically explore form (geometry) and interactivity simultaneously. On the other hand, sub-system prototypes might make more sense in situations where the interactivity of the product is less all-important. [Ulrich and Eppinger 2007] claimed that a combination of comprehensive (Entire system) and analytical prototyping is not feasible. Other researchers have presented examples of how a comprehensive and analytical design is useful in the automotive and maritime industries [Kim et al. 2002], [Wohlke 2005]. [Clark and Fujimoto 1991] exemplified cultural differences in the automotive industry and pointed out that European high-end brands utilize prototypes as "master models" whereas the Japanese car industry uses "prototypes as early problem detectors".

### 3.3 Logistics

'Informational value of prototype' vs. 'Cost of prototype': What, if and how to prototype is a fundamental question to ask. [Thomke 1998] theoretically analysed what he referred to as 'optimal mode switching strategies' to choose between computer simulations (virtual prototypes) vs. physical prototypes. Computer simulations are typically cheap to execute compared to physical prototypes but the physical prototypes possess values that cannot yet be incorporated into the simulations.

Time constraints' vs. 'No time constraints': Researchers have found that time constraints lower the number of solutions proposed but also increase the speed of iterations. Parallel prototyping has been found to be attractive in time constrained environments as a higher quality of design results [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Cost constraints' vs. 'No cost constraints': Experiments show that with cost constraints fewer design solutions are generated. No cost constraints lead to more creative and unusual designs but they increase allocated time [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Resource (material) constraints' vs. 'No resource constraints': Resource constraints have negative impacts on the number of designs proposed but they seem to create a more tangible design task and environment for the designers [Savage et al. 1998], [Dahan and Srinivasan 2000].

'Parallel concepts' vs. 'Single concept': The attractiveness of parallel prototyping is greater when time-to-market is important, when prototyping costs are lower, and when new prototyping technologies are available [Dahan and Mendelson 1998]. If prototypes are to be presented to users, parallel prototyping resolves some residual uncertainty after the concept phase compared to the 'single concept' approach. [Srinivasan et al. 1997]. A second line of research suggests that parallel prototyping requires suitable processes, resources, and organizational structure to be successful [Smith 1991]. Parallel testing proceeds faster than serial testing but does not take advantage of the potential for learning between tests in a single concept approach [Loch 2001].

'Iterative approach' vs. 'Single model per concept': It is generally accepted in product development that an iterative approach obtains better design outcomes [Ulrich and Eppinger 2007]. How to iterate is probably highly case-specific and there is no prototyping tool that supports all areas of investigation [Houde and Hill 1997].

### 3.4 Embodiment

'Virtual models' vs. 'Physical models': Various software tools have been widely used in product development. [Zorriassatine et al. 2003] surveyed the potential for virtual prototyping in mechanical product development, and concluded that virtual tools were being rapidly developed and that the potentials and pitfalls were case-specific. [Dahan and Srinivasan 2000] demonstrated a scenario where virtual prototypes had been used for market share predictions that were nearly identical to those based on physical prototypes. Other research however has shown that physical parts create value, e.g. idea generation, that is not obtained from virtual simulations [Viswanathan and Linsey 2010]. "Designers' mental models of a products' behaviour are often inaccurate or incomplete unless they have extensive experience or training in a particular area." [Viswanathan and Linsey 2010].

'Test (easily available) materials' vs. 'Final (manufacturing) material': In recent years additive manufacturing tools have become widely available. These tools offer new possibilities, although a disadvantage of these technologies is the limited selection of materials that is available. Their product properties also differ from the results of conventional manufacturing methods [Wohlers Associates 2013]. According to [Drezner 1992] “There should be no commitment to production during the prototyping phase.”

‘Outsource work’ vs. ‘Internal resources’: It can be a dilemma to most companies to decide what aspects of product development to outsource. An investigation of rapid prototyping by [Ruffo et al. 2007] proposed that under most circumstances it is the best strategic decision to produce physical parts in-house, using rapid manufacturing techniques [Ruffo et al. 2007]. [Drezner 1992] stated that “Prototype teams should be composed of highly skilled individuals working [in-house] with little or no disturbance.”

### 3.5 Evaluation

‘Relaxed requirements. ‘Requirements as in the final design’: [Camburn 2015] concluded that prototyping with relaxed requirements can save cost and time. [Drezner 1992] however stated that prototypes should be “built with the goal of meeting minimum design requirements … If it is apparent that objective requirements cannot currently be met it is not wise to proceed with prototyping efforts.” [Drezner 1992].

‘Generative nature’ vs. ‘Analytical nature’: Prototypes are used both as generative and analytical tools. From the definitions presented earlier the analytical aspect of prototyping was dominant. This however does not negate the value of generative prototyping, which is especially embraced for idea generation and ‘front end’ activities. The real challenge in prototyping is probably related to matching optimal tool selection and the objectives of generative or analytical prototyping efforts. [Viswanathan and Linsey 2010] stated that “prototypes “assist the designer by supplementing their mental models of how products behave, resulting in higher quality designs.”

## 4. Discussion

### 4.1 Prototype usage, types, purposes and definitions

In view of our findings on how diverse and broad the term prototype has become, it is fair to state that most of the literature reviewed in this paper – with a few exceptions in the section on prototyping strategies - was focused on providing generic information on prototyping. To describe the purpose of prototypes in four overall paragraphs does not adequately describe the complex purposes of prototyping activities, and can provide only mediocre support in an engineering design perspective.

### 4.2 The future of prototyping

The process of decision making in prototyping is likely to become ever more complex in the future, the process of prototyping is changing along more than one dimension. New business models, such as Crowd Funding, are changing the traditional understanding of products and thus the product development processes. Versions of physical products that traditionally would be considered preliminary are being sold as products in a context where ‘prototypes’ become the product. New digital fabrication technologies are becoming available in ‘Open Workshops’, FabLabs and Makerspaces all over the world and through online platforms. If the competitive and innovative companies of the future hope to use effective prototyping, they will need support in their decision making.

### 4.3 Prototyping strategies

[Schrage 2010] stated that “effective prototyping may be the most valuable ’core competence’ that an innovative organization can hope to have” [Schrage 2010]. Our interpretation of this statement is that innovative organisations are good at creating and executing prototyping strategies. The above section on prototyping strategies makes it clear that such decision-making is multidimensional and complex. There is a current lack of explicit knowledge on how to establish prototyping strategies and also how to effectively carry them out. What is required is a holistic overview of strategic decision-making and support tools for understanding, selecting and applying the specific prototyping technologies. They are needed to support product developers in answering questions such as: 1: “What can we learn [from prototyping]?” 2: “What possibilities do we [in our specific situation] have for obtaining knowledge by using prototyping tools?” 3: “When the tools are selected: How do we best make use of them?” Note that these questions have hierarchical levels of abstraction, and that the strategy section in this paper takes initial steps towards answering the second question. In order to provide concrete support on prototyping and to include the current changes within the field does require further research. It is our aim and hope that this overview of prototyping literature, which is focused on how the term is defined and what is known about strategic elements of prototyping, can help researchers and practitioners in making more enlightened decisions on prototyping activities. Further we hope to increase awareness and support further research within the field.

## 5. Conclusion

Prototypes are an important part of the product development process. A review of different understandings, types, purposes and definitions of the term prototypes makes it possible to state that there are two current usages and to define five categories, based on the purposes of prototypes that were identified. There is a lack of research on prototyping strategies, but it was possible to identify how the different aspects relate to the decision-making processes in prototyping. The role and importance of prototyping has been rapidly changing in the recent years, and there is a clear need to develop support tools focusing on prototyping strategies that that can provide a holistic overview of strategic decision-making and the selection and application of specific prototyping technologies.

### References


*Andreasen, M. M., Hansen, C. T., Cash, P., "Conceptual Design", Springer International Publishing Cham, 2015.*

*Avrahami, D., Hudson, S. E., "Forming interactivity: a tool for rapid prototyping of physical interactive products", Proceedings of the 4th conference on Designing interactive systems: processes, practices, methods, and techniques, 2002, pp. 141–146.*

*Beaudouin-Lafon, M., Mackay, W. E., "Prototyping tools and techniques", Human Computer Interaction—Development Process, 2003, pp. 122–142.*

*Buur, J., Andreasen, M. M., "Design models in mechatronic product development", Design Studies, 1989, pp. 155–162.*

*Camburn, B. A., et al., "Methods for Prototyping Strategies in Conceptual Phases of Design", ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2013.*

*Camburn, B. A., et al., "A Systematic Method for Design Prototyping", Journal of Mechanical Design, 2015.*

*Christie, E. J., et al., "Prototyping Strategies: Literature Review and Identification of Critical Variables", ASEE Annual Conferance, 2012.*

*Dahan, E., Mendelson, H., "Optimal parallel and sequential prototyping in product design", Unpublished Manuscript, MIT, 1998.*

*Dahan, E., Srinivasan, V., "The predictive power of internet-based product concept testing using visual depiction and animation", Journal of Product Innovation Management, 2000, pp. 99–109.*

*de Beer, D. J., Barnard, L. J., Booysen, G. J., "Three-dimensional plotting as a visualisation aid for architectural use", Rapid Prototyping Journal, 2004, pp. 146–151.*

*Drezner, J. A., "The Nature and Role of Prototyping in Weapon System Development", RAND Publishing, 1992.*

*Dunlap, B. U., "Active learning module assessment and the development and testing of a new prototyping planning tool", Department of Mechanical Engineering, University of Texas at Austin, 2014.*

*Goldfarb, I., Kondratova, I., "Visual interface design tool for educational courseware", EDMedia, 2004, pp. 1779-1784.*

*Hannah, R., Michaelraj, A., Summers, J. D., "A Proposed Taxonomy for Physical Prototypes", ASME International Design Engineering Technical Conferences, 2008, pp. 231–243.*

*Hardgrave, B. C., Wilson, R. L., Eastman, K., "Toward a contingency model for selecting an information system prototyping strategy", Journal of Management Information Systems, 1999, pp. 113–136.*

*Houde, S., Hill, C., "What do prototypes prototype", Handbook of Human-Computer Interaction, 2, 1999, pp. 367–381.*

*Jangir, S. K., Gupta, N., Agrawal, S., "Evolution and melioration of software management processes", International Journal of Software Engineering and Applications, 2012, pp. 61-83.*

*Jensen, M. B., Balters, S., Steinert, M., "Measuring prototypes-a standardized quantitative description of prototypes and their outcome for data collection and analysis", Proceedings of ICED 15, Vol.2, 2015, pp. 295-308.*

*Kim, H., et al., "Applying digital manufacturing technology to ship production and the maritime environment", Integrated Manufacturing Systems, 2002, 295–305.*

*Kirjavainen, A., Nousiainen, T., Kankaanranta, M., "Prototyping in Educational Game Design", CHI., 2005, pp. 24–27.*

*Krogstie, J., "Model-based development and evolution of information systems: A Quality Approach", Springer Science and Business Media, 2012.*

*Lim, Y.-K., Stolterman, E., Tenenberg, J., "The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas", ACM Transactions on Computer-Human Interaction, (TOCHI), 2008.*

*Lindow, K., Sternitzke, A., "The Evolution from Hybrid to Blended to Beyond Prototyping", Rethink! Prototyping, Gengnagel, C., Nagy, E., Stark, R. (Eds.), Springer International Publishing, 2016.*

*Loch, C. H., "Parallel and sequential testing of design alternatives", Management Science, 2001, pp. 663–678.*

*Otto, K. N., Wood, K. L., "Product Design: Techniques in Reverse Engineering and New Product Development", Prentice Hall Inc., Upper Saddle River, NJ, 2001.*

*Polydoras, S., Sfantsikopoulos, M., Provatidis, C., "Rational Embracing of Modern Prototyping Capable Design Technologies into the Tools Pool of Product Design Teams", ISRN Mechanical Engineering, 2011.*

*Preece, J., Sharp, H., Rogers, Y., "Interaction Design: Beyond Human-Computer Interaction", John Wiley and Sons, 2015.*

*Ravn, P. M., Gudlaugsson, T. V., Mortensen, N. H., "A multi-layered approach to product architecture modeling: Applied to technology prototypes", Concurrent Engineering, 2015.*

*Ruffo, M., Tuck, C., Hague, R., "Make or buy analysis for rapid manufacturing", Rapid Prototyping Journal, 2007, pp. 23–29.*

*Savage, J. C., Moore, C. J., Miles, C., "The interaction of time and cost constraints on the design process", Design Studies, 1998, pp. 217–233.*

*Schrage, M., "The Culture(s) of prototyping", Design Management Journal (former Series), 2010, pp. 55–65.*

*Smith, P. G., "Developing products in half the time", Van Nostrand Reinhold, 1991.*

*Srinivasan, V., Lovejoy, W. S., Beach, D., "Integrated product design for marketability and manufacturing", Journal of Marketing Research, 1997, pp. 154–163.*

*Thomke, S. H., "Managing Experimentation in the Design of New Products", Management Science, 1998, pp. 743–762.*

*Thomke, S. H., "Experimentation Matters: Unlocking the Potential of New Technologies for Innovation", Harvard Business Press, 2003.*

*Ullman, D. G., "The mechanical design process (4th ed)", McGraw-Hill Higher Education, Boston, 2010.*

*Ulrich, K. T., Eppinger, S. D., "Product design and development", McGraw-Hill Higher Education, 2007.*

*van Harmelen, M., "Exploratory user interface design using scenarios and prototypes", People and computers V: proceedings of the fifth conference of the British Computer Society, 1989, p. 191.*

*Viswanathan, V. K., Linsey, J. S., "Physical models in idea generation - Hindrance or help?", Proceedings of the ASME Design Engineering Technical Conference 2010, 2010, pp. 329–339.*

*Wall, M. B., "Making sense of prototyping technologies for product design", Massachusetts Institute of Technology, 1991.*

*Wohlers Associates, "Wohler Report 2013 - Additive Manufacturing and 3D Printing State of the Industry", Annual Wordwide Progress Report, No. ISBN 0-9754429-9-6, 2013.*

*Wohlke, G., "Digital Planning Validation in automotive industry", Computers in Industry, 2005, pp. 393–405.*

*Yang, M. C., "A study of prototypes, design activity, and design outcome", Design Studies, 2005, pp. 649–669.*

*Youmans, R. J., "The effects of physical prototyping and group work on the reduction of design fixation", Design Studies, 2011, pp. 115–138.*

*Zorriassatine, F., et al., "A survey of virtual prototyping techniques for mechanical product development", Proceedings of the Institution of Mechanical Engineers, Part B, 2003, pp. 513–530.*

Lasse Skovgaard Jensen, PhD student
Technical University of Denmark, Department of Mechanical Engineering
Nørre Voldgade 20, 1. th, 1358 København K, Denmark
Email: lsje@dtu.dk

# *Intermediate Results*: Draft; A study of the roles and purposes of prototypes in 13 hardware start-ups

Jensen, Lasse Skovgaard; Özkil, Ali Gürcan

Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

*The work presented in this document is a representation of ongoing work-in-progress. The study is intended for future publication after further analysis, documentation-efforts and alignment with state of the art literature.*

## 1 Introduction

According to scholars focusing their research efforts on prototyping, engineering design research has not been successful in providing designers with formal methods and approaches for prototyping, which especially for inexperienced practitioners result in inefficient use of time and recourses (Menold, 2017), Camburn, 2015).

In order to provide such methods and support, an industry perspective on prototyping is needed (Jensen et al., 2017). Through this study we aim at conveying insights on the role and purposes of prototypes in hardware start-ups. Our empirical data is based on 13 in depth interviews with 13 hardware start-ups in Scandinavia and China. In this light we have outlined the following research questions:

- RQ1: What is the role and purpose of physical prototypes in hardware start-ups?
  - RQ1.2: How do hardware start-ups fabricate prototypes?
  - RQ1.3: How are prototypes exposed (used) by hardware start-ups?

The intermediate results presented in this section differs from the previous studies of prototyping in two major aspects; First, we provide insights on prototyping practices in industry, a current research opportunity recently highlighted by (Deininger et al., 2017) and (Jensen et al., 2017). Second, our analysis is focused on the roles and purposes of physical prototypes in hardware start-ups. A topic that in existing design literature is primarily covered by assessment of project work by student's teams. Such examples are (Zink et al., 2017), (Schmidt et al., 2017), (Böhmer et al., 2017), (Menold et al., 2017), (Christie et al., 2012), (Deininger et al., 2017), (Camburn et al., 2013).

The following sections is structured as follows. In the subsequent section we outline our research methods for this study by outlining the approach used for data collection and analysis as well as the participating start-ups. Next, present our results and provide insights e.g. underlining prototyping as a central product development activity. The third section presents a discussion and reflection and finally we conclude on our findings and outline suggestions for future work.

## 2 Research Methods

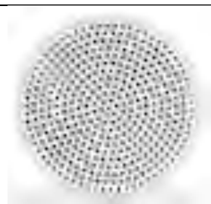
This study was designed to investigate the role and purpose of prototypes and prototyping practices in hardware start-ups. A qualitative research approach was used with the objective to learn from the participant's experiences and also establish an understanding of their conceptions of prototypes and design practices.

Qualitative studies benefit from their ability to facilitate nuanced and detailed exploration of a specific topic (Boyatzis, 1998)(Creswell, 2003)(Patton, 2005). And as highlighted by Deininger et al. such approaches are well-established within design research and studies of the design practices in general (Deininger et al., 2017).

### 2.1 Participants

In order to address the research questions of this study, we approached a selection of hardware start-ups which have all developed and started to market a consumer oriented product. 13 hardware start-ups participated in the study. The start-ups were geographically located in Denmark (7), Sweden (2), Hong Kong (2) and Mainland China (2). In total 21 companies were approached and 13 accepted to participate in the study. A geographically distributed data corpus and products with varying characteristics was prioritized to strengthen the generalizability of the study. We further find that a corpus of this scale is typical for qualitative research studies (Björklund, 2013), (Cash et al., 2012), (Jensen et al., 2017). An overview of the participants is presented in Table 1. Additional product information and representative prototyping photos are illustrated in Table 4.

*Table 1: Overview of the 13 participating hardware start-ups. Photos provided by companies.*

| Product, Company & Interviewee | Product Picture | | Product, Company & Interviewee | Product Picture |
|---|---|---|---|---|
| **Opløft by Lolle & Nielsen**<br>-<br>*Lead Mechanical Engineer* |  | | **Point by Minut**<br>-<br>*Chief Executive Officer* |  |
| **Audiocase by Audiocase**<br>-<br>*Chief Technology Officer* |  | | **Soundboks by Soundboks**<br>-<br>*Head of Development* |  |
| **Sitpack by Sitpack**<br>-<br>*Lead Mechanical Engineer* |  | | **Free Drum by Free Drum**<br>-<br>*Chief Executive Officer* | |

| | | | | |
|---|---|---|---|---|
| **SALTO Pro by ROKOKO Electronics**<br>-<br>*Vice President of Product* |  | | **Marlin by Platysens**<br>-<br>*Head of Development* |  |
| **Mjolnir by Vavuud**<br>-<br>*Chief Technology Officer* |  | | **Welle by Maxus Tech**<br>-<br>*Lead Product Designer* |  |
| **Airtame by Airtame**<br>-<br>*Chief Product Officer* |  | | **Uwear by Uwear**<br>-<br>*Chief Executive Officer* |  |
| **Air Halo by A-One Tech**<br>-<br>*Chief Executive Officer* |  | | | |

In order to develop an overview of the whole product development journey and understand prototyping activities in particular, we identified the ‘ideal’ interviewees as technical founders or co-cofounders of the start-ups. This as they hold major engineering responsibilities and possess a general overview of operational activities within the company. As the start-up companies generally work with small development teams with 2 – 10 developers, the founders were despite administrative responsibilities also emerged in the concrete development tasks. The majority of the interviewees held previous education within the field of engineering or applied sciences and five of them held more than five years of professional experience. A summary of the educational background, educational level experience level, direct engagement in previous product launches and size of the engineering development teams are presented in Table 2.

*Table 2: Summary of background information for the participating start-up Companies*

| **Educational Background** | | | **Experience +5 years** | | **Previous product launch(es)** | | **Advanced education** | | **Start-up Engineering Full Time staff** | |
|---|---|---|---|---|---|---|---|---|---|---|
| Engineering / applied sciences | Humanities / Social Sciences | Fine Arts | Yes | No | Yes | No | Yes | No | Less than 10 | Above 10 |
| 9 | 2 | 1 | 5 | 8 | 5 | 8 | 12 | 1 | 9 | 4 |

## 2.2 Interview protocol

For this study an interview protocol, dedicated semi structured interviews were developed. The protocol was designed to investigate and articulate the participants prototyping activities during their particular product development projects. The protocol was developed iteratively drawing inspiration from previous prototyping studies (Jensen et al., 2017), (Lauff et al., 2017), (Camburn and Wood, 2018) and in particular the interview protocols and taxonomy presented by (Tim and Summers, 2013), (Deininger et al., 2017) and (Hannah et al., 2008). In order to encourage dialogue and shared understanding, descriptive and supportive information were also included in the protocol e.g. timelines, Likert scales, examples of prototype scope, purpose and dimensions (Ulrich and Eppinger, 2007), prototyping design principles (Camburn et al., 2015) and taxonomy characteristics of prototypes (Hannah et al., 2008). Importantly the use of such support also allowed for direct coding of a range of results.

The research team reviewed and refined the questions several times during study development. A mature protocol layout was e.g. tested through a pilot study with a representative start-up team. This led to further refinements of question segmentation and categorization. A further insight was that supportive information helped to support dialogue. The data aggregated from the pilot study is not included in the results.

To ensure comparable data across all interviews the same protocol was used for all interviews. The protocol covered 6 main themes and included a total of 42 questions. An overview of themes and example questions are presented in Table 3 below.

*Table 3: Interview protocol themes and example questions*

| Main Theme | Example Questions |
| --- | --- |
| General company information | - What is the number of employees in the company?<br>- Can you briefly outline the team composition?<br>- When was the company started and what was the motivation?<br>- What is the company vision?<br>- What is the nature of funding and revenue? |
| Interviewee and team backgrounds | - What is the educational background of the team?<br>- Can you provide a few insights on their practical experience?<br>- What are the current focus and responsibilities of the core team members? |
| Product development | - Can you outline the development approach and use of methodology or methods to structure your work?<br>- Can you describe the product development process and the line of order that brought your product to life?<br>- Did you encounter any project specific challenges? What worked well? What would you maybe do different another time? |
| Perception of prototypes and prototyping | - Could you please define what you think a prototype is?<br>- Could you please define what you think a prototype does?<br>- What has been the purpose of prototyping in this project?<br>- If possible, what would be your definition of a prototype? |
| Fabrication of prototypes | - What do you do in house?<br>- What do you outsource?<br>- Can you try to walk through, what the process would look like for defining and fabricating a prototyping? |
| Prototyping strategies | - When do you prototype?<br>- How do you prototype?<br>- What do you prototype? |

## 2.3 Data collection and analysis

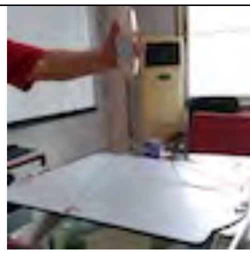
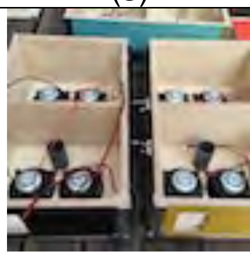
The interviews lasted from 73 minutes to 118 minutes with an average length of 94 minutes. Interviews were conducted at the companies' premises and included an additional tour around the company facilities with a particular focus on office facilities, in-house fabrication tools and test facilities. The interviews followed the interview protocol introduced above but also allowed for follow-up questions for clarification purposes and to encourage further elaboration and dialogue. A single member of the research team conducted all 13 interviews and were in four cases accompanied by an additional team member.

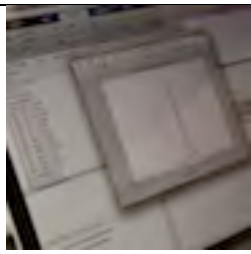
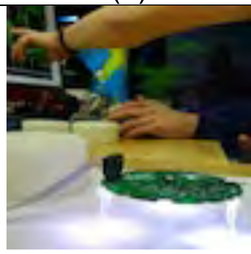
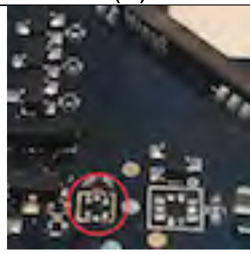
During and preceding the interviews, the data collected were summarized in detailed notes. The interviewees reviewed these notes and verified their accuracy and reliability. Finally, the interviews were audio recorded and subsequently coded to establish themes and other relations. The coding process draws on approaches conducted in existing prototyping focused literature. This including categorizations of prototype definitions according to five themes and 14 sub themes as conducted by Lauff et al. (Lauff et al., 2017) and the taxonomy introduced by Hannah et al. (Hannah et al., 2008). The results of the coding process are further reflected in the in the presentation of our results where our findings are summarized. In the followings section presenting the results of our analysis, the specific start-ups are anonymized due to discretion requirements demanded by some of the participating teams.

# 3 Results

In the following paragraphs we present our results. To support the contextual understanding we include, in Table 4, an overview of the products developed by the hardware start-ups participating in the study and also a range of descriptive photos of design and prototyping activities.

*Table 4: Overview of products and examples of prototyping and prototype fabrication. Combination of personal photos and photos provided by participating companies*

| Product & Company | Product Description | Examples of prototyping and prototype fabrication | | |
|---|---|---|---|---|
| Opløft by Lolle & Nielsen  | Height adjustable tabletop product |  (1) |  (2) |  (3) |
| Audiocase by Audiocase  | Portable Bluetooth speaker |  (1) |  (2) |  (3) |
| Sitpack by Sitpack  | Collapsible chair |  (1) |  (2) |  (3) |
| SALTO Pro by ROKOKO Electronics | Sensor based Motion Capture Suit |  (1) |  (2) |  (3) |

| | | | | |
|---|---|---|---|---|
| Mjolnir by Vavuud  | Smartphone wind meter |  (1) |  (2) |  (3) |
| Airtame by Airtame  | Wireless HDMI dongle |  (1) |  (2) |  (3) |
| Point by Minut  | Sensor based Home security device |  (1) |  (2) |  (3) |
| Soundboks by Soundboks  | High performance wireless speaker |  (1) |  (2) |  (3) |
| Free Drum by Free Drum | Digital and sensor based drum kit |  (1) |  (2) |  (3) |
| Marlin by Platysens  | Wearable device for open water swimming |  (1) |  (2) |  (3) |

| | | | | |
|---|---|---|---|---|
| Welle by Maxus Tech  | Gesture controlled input device |  (1) |  (2) |  (3) |
| Uwear by Uwear  | Smartwatch for hikers |  (1) |  (2) |  (3) |
| Air Halo by A-One Tech  | Plasma technology air cleaner |  (1) |  (2) |  (3) |

## 3.1 Definitions of prototypes

In order to understand how the interviewees defined prototypes, we asked them to explain their view on how prototypes could be defined. We here received reflections covering a wide spectrum of characteristics. Common reflections were that prototypes are unfinished versions of a future product. Also, the majority of interviewees provides examples, such as the ones introduced by (Einstein, 2015). Respectively Proof-of-concept-prototypes, Looks-like prototypes, Works-like prototypes and Engineering prototypes. This underlines that prototypes are understood as design tools that can embody various forms and shapes and also mimic various different product characteristics.

Our subsequent coding reflects that 10 of the 13 interviewees provided a point of view, which we previously have characterized as a 'total prototype' view. Here prototypes are defined very broadly and every model representing a product or idea can be referred to as a prototype (Jensen et al., 2016). The remaining 3 interviewees presented a more 'traditional engineering point of view', where prototypes are defined as 'high fidelity models' and is generally intended for some aspect of testing.

## 3.2 Roles and purpose of prototypes

Prototypes take up different roles in the product development process and the purpose of their application in the design activities is multifaceted. With offset in the five themes and 14 sub-themes provided by Lauff et al. (Lauff et al., 2017), we coded our data body. This to understand purposes and roles of prototypes in the start-up companies. The results of this coding process is presented in Table 5.

*Table 5: Coded results on overall roles and purposes of prototypes*

| Theme | Sub-Theme | Partial Example Responses | Coding results |
|---|---|---|---|
| Build/test | Materials | "to ensure the correct materials" | 8 |
| | Components | "to build and test aspects of the design" | 12 |
| | Users | "to understand if this meets user needs" | 7 |
| Functionality | Technical aspects | "to test functionality" | 12 |
| | Integration | "to ensure the whole system works" | 13 |
| Decision Making | Concepts, ideas | "to refine a concept" | 9 |
| | Business-related | "to determine viability of the design" | 5 |
| | Product | "to decide on aspects of the design" | 12 |
| | Process | "to finalize production processes" | 12 |
| Communication | Explain, Demonstrate | "to show the team" | 12 |
| | Persuade, Negotiate | "to have the project manager agree" | 10 |
| | Visualize | "to better understand the design in 3D" | 10 |
| Learning | Prior knowledge | "to see if the concept works" | 13 |
| | New knowledge | "to learn about new materials" | 8 |

The results presented in Table 5 documents that prototypes are used for various purposes. The most often coded theme is functionality with the two sub themes of technical aspects and integration, which was coded for respectively 12 and 13 teams.

Only five of the 14 codes were not coded for 10 or more of the teams – though all codes were identified at least five times. The least frequent codes represents i) to build and test prototypes focused on materials and material properties, ii) to refine a concept or idea with the purpose of decision-making, iii) to build prototypes for viability / business related decision making, iv) to build and test prototypes with the purpose of understanding user needs, and v) to prototype with the ambition to obtain new knowledge e.g. by exploring the design.

The interviewees generally argued that they were very actively making use of prototypes and considered it as a central design tool. Two exemplary quotes are presented below:

- "We build prototypes every time we are uncertain about something and then we test it."
- "We build prototype of all design changes."

Three teams were more focused in their reported prototyping efforts. Here exemplified through the following quote:

- "We often use prototypes and I would say that we mainly focus at verifying that parts [Red. sub-systems] fit together or simply testing functionality"

An important understanding obtained from our interviews was that the purpose of prototyping was often described through what we chose to describe as ‘a hierarchical understanding’. The interviewees described how prototypes were fabricated/ordered to test or learn about a certain design aspect, but later were used for other purposes such as communication with the team. Two exemplary quotes are presented below:

“A prototype might originally be fabricated for a specific test. But bringing the prototypes to a meeting and showing results help reduce everyone’s personal bias’. We start talking about thing we know [Red. results of prototyping activities] rather than our opinions.”

“For communication prototypes are important discussion mediators. They help me bring the facts to the table. We look at our prototypes when we have collected feedback from users or a design layout that failed. Hereby we can mediate our personal opinions and stop defending our ‘darlings’.

## 3.3 Fabrication of prototypes

The following section provides overall insights on how prototypes were fabricated by the participating start-ups. Strategic decisions on how to fabricate prototypes are part of the prototyping strategy and prototype fabrication is both a subset of the skills for materializing prototypes and an activity which can support e.g. experimentation in the design process. In Figure 1 below we report on how prototypes were fabricated in the start-ups.

In our categorization we overall differentiate between ‘DIY fabrication’ and ‘external fabrication services’. The first includes designers fabricating the prototypes. This either at the start-ups own facilities or at local makerspaces and fablab’s. The later, refers to the use of dedicated fabrication services. Further we differentiate between the notion of ‘early stage design’ and ‘mature stage design’. These referring respectively to; research clarification, design exploration concept development and selection. ‘And; embodiment and detailed design including design verification moving towards manufacturing.

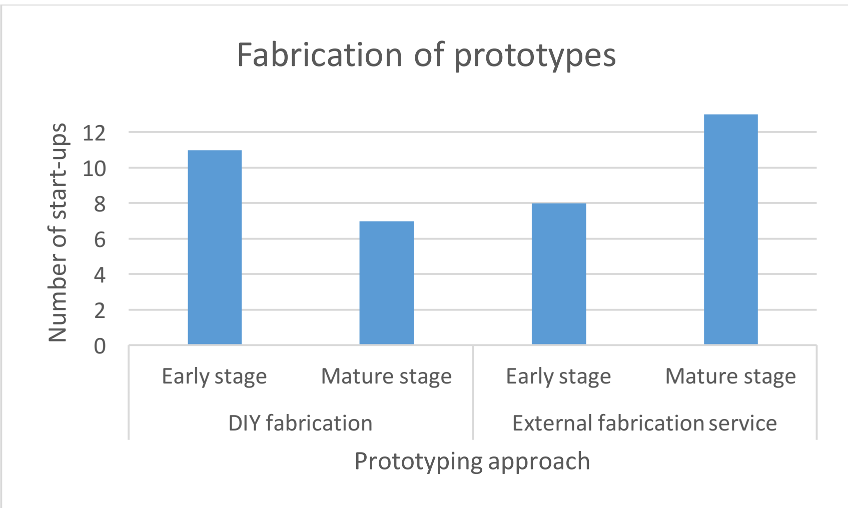



*Figure 1: Approach to fabrication of prototypes*

Figure 1 presents the finding that especially for early stage design, DIY fabrication is performed, whereas all 13 start-ups made use of external fabrication services for activities in the later stages of the design process.

For DIY fabrication the following tools were reported as mainly used:
- 11 start-ups reported to use 3d printing.
- 8 start-ups used hand soldering.
- 6 start-ups made printed circuit boards in house.
- 5 start-ups used hand held power tools.
- 4 start-ups used laser cutters.

For external fabrication in particular two services were commonly used:

- 10 start-ups used services for high quality 3d prints from the teams own CAD files – generally parts fabrication by more delicate technologies than the standard desktop FDM technology.
- 9 start-ups used services for small order quantities of printed circuit boards based on layouts of the teams own designs.

For both of these types of services there was a general agreement that the workflow was well functioning. Especially the Chinese teams described the process as highly effective and often with options to have such high resolution prototypes delivered within a timeline of as little as 24 hours.

A third category can also be identified as 'specialized manufacturers'. The majority of the products realized by the teams contains custom parts that were designed by utilizing prototypes. Such prototypes were made though collaboration with stakeholders specialized in a particular manufacturing domain. Examples are custom fabrics, special cable connectors, knobs and buttons, injection molded plastic parts, heatsinks and the like. These 'specialized manufacturers' are spread over a wide range of industries and the start-ups articulated it as a comprehensive process to identify and locate suitable partners for supplying these prototypes. Only design teams that had prior experience from other projects in the same industry did not underline the substantial efforts invested in this task.

In a few cases these the relationship with these 'specialized manufacturers' developed over time and have also become manufacturing partners. In two cases the manufacturing partner further evolved into a role as venture capital investment partner for the start-up.

Below we provide exemplary quotes on prototype fabrication:
- "Tinkering around with prototypes fabricated here in the office helped us to explore our technology and understand how parameters interact and relate."
- "The precision of our prototypes were not the central aspect in this stage [Red. Early stage] of the project."
- "When we proceeded from a proof of concept, we made the conclusion that outsourcing all complex prototype fabrication was the best option. This was for two

reasons: First, the effort it takes in time and recourses to fabricate in-house does simply not pay off compared to ordering high quality parts from dedicated prototyping agencies. Second, when refining our technology, we needed prototypes with performance like mass manufactured parts."

## 3.4 Prototypes as boundary objects and tools for knowledge transfer

The notion that prototypes can support communication and function as boundary objects is not a new observation (Subrahmanian et al., 2003). Our findings do though expand such concepts. Five start-ups reported to use prototypes as shared documentation and version control tools. Information which has historically been stored and shared as written documentation. Below we provide three exemplary quotes to characterize this approach:

- "We actually have a document for version history control, but we don't use it. We just update or order a new prototype. Then everyone refers to it here at the office."

- "I start the 3d printer every day when I leave the office. Every morning I have an updated design at my desk. People come by to look at it and I like the dialogue and feedback."

- "I order prototypes of all my designs and stores them in a box at my desk with a dated sticker attached. It's cool to see the progress."

- "When communicating with our manufacturing partner, we send photo and video material of our prototypes along with annotations and guidelines. Such function much smoother than spec sheets which can be kind of de-coupled from the product."

These quotes are representative of two mechanisms:

The first is how prototyping are supporting collaboration and shared problem understanding in design teams and provide a sense off forward progress in the design project. Such have also previously been identified by (Gerber, 2009) (Gerber and Carroll, 2012) (Vetterli et al., 2012).

Second, the reported activities and actions can be described as approaches to enable codification and transfer of inherit tacit knowledge that is being transferred to other team members or external stakeholders. Such inline well with Erichsen et al., who argue that prototypes impact on knowledge acquisition and transfer could be a potential future research topic (Erichsen et al., 2016).

## 3.5 Support tools

Interviewees were asked if they utilized any frameworks, checklists or specific planning approaches for their prototyping activities. The question was elaborated by giving examples on areas where tools might be applied: e.g. i) To formulate design questions, ii)

To plan how to fabricate prototypes, iii) To define an appropriate approach for how to test or make use of the prototype.

In all thirteen cases the interviewees argued that no formalized tools were used. Generally, it was explained that teams drew on experiences from previous projects.

For concrete fabrication activities six interviewees reported that they – or team members – often followed fabrication 'cookbook' guidelines from instructables.com or other online media providing instructions for fabrication.

Our findings echo what have previously been stated by Bradley Camburn; "Many designers state that prototype planning occurs according to experience or intuition. There are limited tools to guide the development of prototyping efforts or to give insights on how to design and fabricate prototypes with higher efficiency" (Camburn, 2015).

### 3.6 'Design by prototyping'

From the interviews a range of observations and patterns emerged, which we in their combination do not find well expressed in the existing literature. This in particular among six design teams, which all described their definitions of prototypes very broadly and reported activity use of prototypes for their design activities. In this section we aim at summarizing these observations in six characteristics:

- Prototyping is the designers 'weapon of choice' and language of expression.
- Design propagates from prototype to prototype and prototypes serve various purposes
- Prototypes facilitates increased 'product understanding', version control mechanics and richer collaboration.
- Prototypes function as boundary objects to mediate uncertainty and personal bias in decision-making.
- Prototyping is catalyst for codifying and transferring tacit knowledge.
- Designers utilize opportunities of digital fabrication and DIY design repositories, but also manufacturing services.

We have identified the combination of these characterizes among six of the study participants. This introduces some restrictions regarding their generalizability, however also points to a particular trend among some hardware start-ups who practice a particularly prototype driven development culture. In the following discussion we present further reflections on this result.

# 4 Discussion and Reflections

This section presents a discussion and reflections of our results.

## 4.1 Definitions of prototypes

We have introduced how the vast majority of the teams use broad definitions of the term 'prototype'. In the literature, other definitions exists and alternative terminology use terms such as 'Experimental set-up', 'Design mock-ups', 'Function models' and 'pre-production series' to describe a progression in model fidelity throughout the design process (Buur, 1989). We find that these terms were generally not unknown to the interviewees, but 'passive terms' in their vocabulary. We further find that the terms looks-like prototypes and works-like prototypes etc. are more frequently used in popular blogs and online media by practitioners and consultancies within the start-up community ("Dragon Innovation," 2016),(Einstein, 2015).

## 4.2 Role and purpose of prototypes

The results documented in this study for the roles and purposes of prototypes are more equally distributed over the five themes than the ones originally presented by Lauff et al., who compare students and professionals though data primarily based on surveys (Lauff et al., 2017). They found that both students and professionals used prototypes to build and test concepts around functionality. Students' heavily favored the idea that prototypes are used to be built and then tested for elements of functionality. Professionals, on the other hand, indicated that prototypes are also used for decision making, communication, and learning. This substantially more often than students. This variation in findings can be rooted in different reasons. One possibility is that start-ups utilize prototypes for different purposes. Another possibility can be the difference in how the studies are conducted.

## 4.3 'Design by prototyping'

When proposing the identification of a particular product development approach, we should also exemplify how this approach is not sufficiently encapsulated by existing paradigms. Below we provide three examples:

- The term 'prototrialing' was recently introduced by (Jensen et al., 2017), and is characterized by use of high-functional prototypes of low fidelity in early stage concept development. The terms thus different as 'Design by prototyping' is not limited to early stage development nor focused particularly at high-functional prototypes of low fidelity.

- Design thinking is a human-centric methodology integrating expertise from design, social sciences, business and engineering (Leifer and Steinert, 2014). Design thinking has a strong focus on various aspects of prototyping (Kelley and Littman, 2001). In this sense design thinking and design by prototyping shares and overlap in the mindset being applied, but design thinking is also a comprehensive term encompassing various cognitive and practical activities (Cross, 2001). In this light we adopt the argument proposed by Christie, that design thinking does not present in-depth insights on prototyping (Christie et al., 2012).

- An alternative to physical prototyping is sketching, and a segment of designers also identify sketching as their ‘weapon of choice’ hereby many similar characteristics could potentially by identified. We do though argue that the restrictions of two-dimensionality and recent advancements in the fabrication technologies often used for prototyping is increasing the gap between the two approaches. Design by prototyping hereby encompasses a wider palette of opportunities then those which can be successfully pursued through the use of sketching.

Our identification of this approach is work in progress and we allow ourselves to think out loud. It is our hope that research peers see value in it and will take part in building on our understanding of how hardware start-ups use prototypes.

Limitations for our understanding are that it is established solely from the hardware start-up community, which might have particular characters that does not generalize to all organization. Examples are I) the limited size and physical location of design teams, limits the need for formalized written documentation. Ii) Organizations with no previous product introductions might highly dependent on prototypes. Iii) The often limited experience of design teams might put particular focus on prototyping to support understanding if concept will work.

## 4.4 Regional differences

As reported in the methods section, the interviews for this study was conducted in Scandinavia (Denmark and Sweden) and China (Hong Kong and Shenzhen). Some preliminary patterns in regional difference were observed by the research team. First of all, the start-ups in china reported more focused prototyping efforts with a clear purpose, but also restricted their efforts to mainly testing and verifying design decisions, with less focus in other dimensions such as a communication. A particular focus at manufacturing related decisions, already during early conceptualization, were observed. The Chinese start-ups further managed to conclude the fastest development cycles in bringing their products to the market.
Other studies have previously documented how product development processes in this region is inspired from the fast paced concept of ‘shanzhai manufacturing’, where a highly integrated and interconnected manufacturing and development network focuses on counterfeit products and product remixes of consumer electronics (Lindtner et al., 2015), (Shi and Zhu, 2010).
Due to our limited dataset we will refrain from generalizing on these observations, but simply note that the geographical proximity to the city of Shenzhen and surrounding manufacturing power-house might influence development focuses.

## 4.5 Limitations of the study

Interviews like the ones conducted for this study are hindsight reflections on designers own practices. Whereas this might enable the interviewees to provide more elaborate reflections it also introduces the possibility of biased statements. Further, we interviewed only one team member as representative for the (though small) design teams. Other limitations include the limited sample size, and as with all qualitative research, there is a possibility that perspectives or insights were not identified during data collection and analyses.

## 5 Conclusion

This study presents the results of interviews on prototyping conducted with 13 hardware start-ups in Scandinavia and China. The study is focused on the role and purposes of prototypes and how prototypes are fabricated throughout the design process.
We find that prototypes can serve multiple purposes varying over the themes build/test, functionality, decision making, communication and learning. It is further identified how prototypes serves as tools to collaborate and codify tacit knowledge and also supports version control mechanisms. In the early stage design, these prototypes are primarily fabricated by the design teams, whereas all teams in the later design stages used fabrication services for prototyping.
Finally, we identify a particular prototype driven development approach being practiced by a range of the participating start-ups.

## References


Björklund, T.A., 2013. Initial mental representations of design problems: Differences between experts and novices. Des. Stud. 34, 135–160.

Böhmer, A., Kayser, L., Sheppard, S., Lindemann, U., 2017. Prototyping as a thinking approach in design.

Boyatzis, R.E., 1998. Transforming qualitative information: Thematic analysis and code development. sage.

Buur, J., 1989. Design models in mechatronic product development. Des. Stud. 10, 155–162. https://doi.org/10.1016/0142-694x(89)90033-1

Camburn, B., Wood, K., 2018. Principles of maker and DIY fabrication: Enabling design prototypes at low cost. Des. Stud. https://doi.org/10.1016/j.destud.2018.04.002

Camburn, B.A., 2015. Design prototyping methods (PhD Dissertation). The University of Texas at Austin.

Camburn, B.A., Dunlap, B.U., Kuhr, R., Viswanathan, V.K., Linsey, J.S., Jensen, D.D., Crawford, R.H., Otto, K., Wood, K.L., 2013. Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment, in: ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V005T06A033–V005T06A033.

Camburn, B.A., Sng, K.H., Perez, K.B., Otto, K., Wood, K.L., Jensen, D., Crawford, R., 2015. THE WAY MAKERS PROTOTYPE: PRINCIPLES OF DIY DESIGN. Extraction 41, 42.

Cash, P., Elias, E., Dekoninck, E., Culley, S., 2012. Methodological insights from a rigorous small scale design experiment. Des. Stud. 33, 208–235.

Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L., Crawford, R.H., 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables, in: American Society for Engineering Education. American Society for Engineering Education.

Creswell, J.W., 2003. Research design: qualitative, quantitative, and mixed method approaches, 2nd ed. ed. Sage Publications, Thousand Oaks, Calif.

Cross, N., 2001. Chapter 5 - Design Cognition: Results from Protocol and other Empirical Studies of Design Activity, in: Eastman, C.M., McCracken, W.M., Newstetter, W.C. (Eds.), Design Knowing and Learning: Cognition in Design Education. Elsevier Science, Oxford, pp. 79–103. https://doi.org/10.1016/B978-008043868-9/50005-X

Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., 2017. Novice designers' use of prototypes in engineering design. Des. Stud. 51, 25–65. https://doi.org/10.1016/j.destud.2017.04.002

Dragon Innovation, 2016. . Dragon Innov. Blog.

Einstein, B., 2015. The Illustrated Guide to Product Development (Part 1: Ideation) [WWW Document]. Bolt Blog. URL https://blog.bolt.io/the-illustrated-guide-to-product-development-part-1-ideation-ab797df1dac7#.harn8xqx4 (accessed 11.22.16).
Erichsen, J.A.B., Steinert, M., Pedersen, A.L., Welo, T., 2016. Using Prototypes to Leverage Knowledge in Product Development: Examples from the Automotive Industry. 2016 Annu. Ieee Syst. Conf. Syscon 485–490.
Gerber, E., 2009. Prototyping: facing uncertainty through small wins, in: DS 58-9: Proceedings of ICED 09, the 17th International Conference on Engineering Design, Vol. 9, Human Behavior in Design, Palo Alto, CA, USA, 24.-27.08. 2009.
Gerber, E., Carroll, M., 2012. The psychological experience of prototyping. Des. Stud. 33, 64–84. https://doi.org/10.1016/j.destud.2011.06.005
Hannah, R., Michaelraj, A., Summers, J.D., 2008. A Proposed Taxonomy for Physical Prototypes: Structure and Validation, in: ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. 231–243.
Jensen, L.S., Özkil, A.G., Mortensen, N.H., 2016. Prototypes in engineering design: Definitions and strategies, in: DS 84: Proceedings of the DESIGN 2016 14th International Design Conference.
Jensen, M.B., Elverum, C.W., Steinert, M., 2017. Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. Des. Stud. 49, 1–31. https://doi.org/10.1016/j.destud.2016.12.002
Kelley, T., Littman, J., 2001. The art of innovation : lessons in creativity from IDEO, America's leading design firm. Currency/Doubleday.
Lauff, C., Kotys-Schwartz, D., Rentschler, M.E., 2017. Perceptions of Prototypes: Pilot Study Comparing Students and Professionals. ASME, p. V003T04A011. https://doi.org/10.1115/DETC2017-68117
Leifer, L.J., Steinert, M., 2014. Dancing with Ambiguity: Causality Behavior, Design Thinking, and Triple-Loop-Learning, in: Gassmann, O., Schweitzer, F. (Eds.), Management of the Fuzzy Front End of Innovation. Springer International Publishing, pp. 141–158. https://doi.org/10.1007/978-3-319-01056-4_11
Lindtner, S., Greenspan, A., Li, D., 2015. Designed in Shenzhen: Shanzhai Manufacturing and Maker Entrepreneurs, in: Proceedings of The Fifth Decennial Aarhus Conference on Critical Alternatives, AA '15. Aarhus University Press, Aarhus, Denmark, pp. 85–96. https://doi.org/10.7146/aahcc.v1i1.21265
Menold, J., Jablokow, K., Simpson, T., 2017. Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. Des. Stud. 50, 70–112.
Menold, J.D., 2017. Prototype For X (PFX): A Prototyping Framework to Support Product Design (PhD Dissertation). The Pennsylvania State University.
Patton, M.Q., 2005. Qualitative research. Wiley Online Library.
Schmidt, T., Wallisch, A., Böhmer, A., Paetzold, K., Lindemann, U., 2017. Media Richness Theory in Agile Development: Choosing Appropriate Kinds of Prototypes to Obtain Reliable Feedback.
Shi, Y., Zhu, S., 2010. Shanzhai manufacturing – an alternative innovation phenomenon in China: Its value chain and implications for Chinese science and technology policies. J. Sci. Technol. Policy China 1, 29–49. https://doi.org/10.1108/17585521011032531
Subrahmanian, E., Monarch, I., Konda, S., Granger, H., Milliken, R., Westerberg, A., Group, T., 2003. Boundary Objects and Prototypes at the Interfaces of Engineering Design. Comput. Support. Coop. Work CSCW 12, 185–203. https://doi.org/10.1023/A:1023976111188
Tim, H., Summers, J.D., 2013. CASE STUDY: EVIDENCE OF PROTOTYPING ROLES IN CONCEPTUAL DESIGN. Presented at the ICED.
Ulrich, Eppinger, 2007. Product design and development. McGraw-Hill Higher Education.
Vetterli, C., Hoffmann, F., Brenner, W., Eppler, M.J., Uebernickel, F., 2012. Designing innovation: Prototypes and team performance in design thinking, in: ISPIM Conference Proceedings. The International Society for Professional Innovation Management (ISPIM), p. 1.
Zink, L., Böhmer, A., Hostettler, R., Lindemann, U., Knoll, A., 2017. The use of prototypes within agile product development.

Design Science

# Identifying challenges in crowdfunded product development: a review of Kickstarter projects

Lasse Skovgaard Jensen[1] and Ali Gürcan Özkil[1]

1 *Technical University of Denmark, Department of Mechanical Engineering, Section of Engineering Design and Product Development, Produktionstorvet Building 426, 2800 Kgs. Lyngby, Denmark*

LSJ, http://orcid.org/0000-0001-7524-9941

## Abstract

This paper provides an empirical review of the reward-based crowdfunding platform Kickstarter.com, with the aim to explore and identify challenges in crowdfunded product development, which consequently can lead to failure of the crowdfunding campaign. The review was based on the analysis of a total of 144 successfully funded 'technology' campaigns, which all concerned the creation of physical consumer hardware preordered by campaign backers. The analysis was built around a failure mode model, which was established through a pre-study. The study reveals that (i) no more than 32% of the campaigns managed to deliver the crowdfunded products on time, and, if campaigns are delayed, (ii) there is a significantly higher probability that the delivered products might lack expected attributes. The causes for delay have many reasons, but (iii) a set of particular product development issues were identified as the main challenges. A better understanding of crowdfunded product development can help researchers and practitioners to better understand and utilize the opportunities of this new product development paradigm.

**Key words:** product development, crowdfunding, Tech. entrepreneurship

Received 28 November 2017
Revised 13 September 2018
Accepted 24 September 2018

Corresponding author
L. S. Jensen
lsje@mek.dtu.dk

Published by Cambridge University Press
© The Author(s) 2018
Distributed as Open Access under a CC-BY 4.0 license (http://creativecommons.org/licenses/by/4.0/)

*Des. Sci.*, vol. 4, e18
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2018.14

the Design Society
a worldwide community

CAMBRIDGE UNIVERSITY PRESS

## 1. Introduction

Crowdfunding platforms have become widely popular in the past few years (Massolution 2015). Despite the broad focus of the existing platforms, which host projects on themes including everything from technology to the arts, technology- and design-oriented hardware products are among the main drivers on these crowdfunding platforms. Take for instance Kickstarter.com, which is self-reported as the world's largest crowdfunding platform. Since its launch in 2009, more than 10,000 hardware projects have been successfully crowdfunded, and campaign backers have in all together pledged more than $3 billion (Kickstarter.com 2016).

According to design and technology curators at Kickstarter, a number of campaigns and related products, would never have been funded by managers and investors in the established industry (Yulman *et al.* 2017). In this sense, crowdfunding is 'changing what gets made and who has the opportunity to make it' (Yulman *et al.* 2017). This change is facilitated by the platform dynamics, where campaign initiators are connected with the community of backers. This community represents both a demand for new tech products and an



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

interest in 'behind the scenes' insights into the product development journey, from concepts and early prototypes to real products (Belleflamme, Lambert & Schwienbacher 2014).

Crowdfunding enables entrepreneurs to verify their ideas and to raise capital to develop new and innovative products, but the dynamics of crowdfunding, combined with the often limited experience and resources of the development teams, can bring new challenges to the design of crowdfunded products. Campaigns might get delayed or canceled; promised features may be withdrawn or the quality of the products expected by the backers might not be met. Crowdfunding is still a relatively new phenomenon in design research. This study sets out to investigate the phenomenon 'crowdfunded product development', which we define as the product development project taking place in the context of a crowdfunding campaign. Through an analysis of funded campaigns, we explore and identify the challenges that are associated with reward-based crowdfunding at Kickstarter.com. Here, we respectively identify and quantify both: (i) issues that occur during the product development process and (ii) issues regarding the delivered products reported by the backers.

## 1.1. Research focus

Crowdfunding attracts the general public to support the design and development of new and innovative products. The approach provides a venue for entrepreneurs to validate their ideas and to raise capital to cover costs associated with the development, manufacturing and fulfilment of their products. However, the dynamics of crowdfunding, combined with the often limited experiences and resources of the development teams, brings new challenges.

Crowdfunding is still a relatively new phenomenon in design research and this study sets out to investigate 'crowdfunded product development'. Through an analysis of funded campaigns, the goal of this paper is to explore and identify the challenges that are associated with 'crowdfunded product development' and identify what challenges may lead entrepreneurs to fail to deliver the promises announced during campaigns.

The main focus of this paper is on the design, development and fulfilment phases after a crowdfunding campaign gets funded, with the aim of understanding:

(i) *RQ1: What product development issues are reported by campaign initiators of successfully funded reward-based crowdfunding campaigns, as causes for failing to deliver on their promises?*
(ii) *RQ2: How do backers evaluate rewards from campaigns, that also developed and shipped their products, in terms of promised features and product quality?*
(iii) *RQ3: To what extend can particular product development implications or relations between RQ1 and RQ2 be identified as a cause for failure?*

Our study is based on analysis of a data corpus of 144 successfully funded crowdfunded campaigns that aimed to develop consumer-oriented hardware products. All campaigns were based on a 'reward-based' 'all or nothing' principle and the products were hereby 'preordered' by the campaign backers. The data was collected from kickstarter.com and contains a wide range of variables such as total funding, campaign period, delivery timeline, campaign updates, and comments provided by the campaign initiators and backers. Of the 144 campaigns studied, 30 was analyzed in a pre-study focused at conceptualizing a failure



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

mode model (FMM). The FMM was developed to assess campaigns from a longitudinal perspective, and we have systematically analyzed a further 114 campaigns, and identified the design-related issues that were faced during the product development process.

### 1.2. What is crowdfunding?

In broad terms, crowdfunding refers to collecting small amounts of capital from a 'crowd' or relatively large number of people, with the aim of funding entrepreneurial activities. While there are historical examples of crowdfunding, such as the partial construction of the Statue of Liberty (Harris 1985), the modern concept of crowdfunding is rather new and is tightly coupled with the emergence of the Internet, digital communication technologies and online social networks (Schwienbacher & Larralde 2010; Mollick & Kuppuswamy 2014).

According to Haas *et al.* the value proposition of the moderating crowdfunding platform can widely differ (Haas, Blohm & Leimeister 2014). It can be based on hedonism, where backers pledge for new innovations in products or creative projects. Here backers receive a non-monetary return in form of preordered products or rewards. It can be also based on altruism, which primarily aim to support charitable projects. This type of crowdfunding is dominated by donations, and compensations do not exceed tokens of appreciation. Finally, the value proposition can be for profit, which until today have generally been focused on the funding of start-ups, where the backers are offered monetary returns on their venture capital investments.

Generally, crowdfunding involves three types of actors: (i) the project initiator(s) who propose the offering or campaign to be funded, (ii) individuals (backers) who support the idea of the offering and (iii) a moderating organization that provides a communication platform and binds the parties together (Ordanini *et al.* 2011). The initiators range from single individuals to big organizations, but small entrepreneurial teams are behind the majority of crowdfunding campaigns (Mollick & Kuppuswamy 2014).

As noted, backers can be offered different types of value in return for their support. Massolution have proposed a classification that differentiates between four different types of crowdfunding, respectively (Massolution 2012):

(1) Reward-based crowdfunding; in which backers 'primary objective for funding is to gain a non-financial reward, such as a token of appreciation or in the case of a manufactured product, a first edition release.
(2) Lending-based crowdfunding; in which backers receive fixed periodic income and expect repayment of the original principal investment.
(3) Donation-based crowdfunding; in which backers donate to causes they want to support, with no expected compensation.
(4) Equity-based crowdfunding; in which backers receive compensation in the form of equity-based revenue or profit share arrangements.

By 2015, it was estimated that the global crowdfunding market was $16.2 billion, of which $2.68 billion originated from reward-based crowdfunding (Statista 2018). The focus of this study is on reward-based crowdfunding and the actual preordered products that the campaigns offered to backers, which excludes the type of rewards known as 'tokens of appreciation' (Kuppuswamy & Bayus 2015)



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

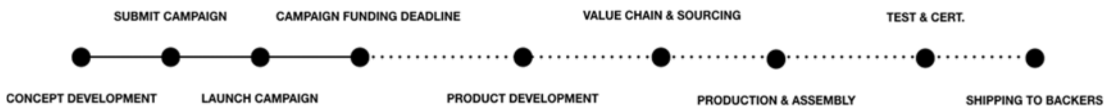



**Figure 1.** Overview of nine main topics of a reward-based crowdfunding campaign timeline. The funding deadline of the campaign represents the 'all or nothing deadline'. This is indicated by the transition to a dotted line as only successfully funded campaigns go through the remaining steps. The figure is based on observations by the authors.

such as 'Thank You' letters, postcards or t-shirts. In reward-based crowdfunding primarily two models are being practiced, 'keep it all' and 'all or nothing'. 'Keep it all' involves the campaign initiators setting a fundraising goal and keeping the entire amount raised, regardless of whether or not they meet their goal. The 'all or nothing' model involves the campaign initiators setting a fundraising goal and keeping nothing unless the goal is achieved (Cumming, Leboeuf & Schwienbacher 2015). This study is focused on the 'all or nothing' model which is e.g. practiced at Kickstarter.com. Figure 1 below presents a theme-based timeline of what the process of a crowdfunding campaign looks like for the 'all or nothing' principle.

Finally, reward-based crowdfunding is not to be confused with related and linked phenomena's. Examples hereof are 'crowdsourcing' (Brabham 2008), where the creative solutions of a distributed network of individuals are harnessed through an open call for proposals. Likewise topics like 'social product development' (Forbes & Schaefer 2017) and 'open innovation' (Chesbrough 2003) has the potential to share respectively the 'socially inclusive' and the 'open' dimensions of product development, but should be considered as prerequisites.

## 1.3. Crowdfunding in research

The recent boom in activity on the crowdfunding platforms has made crowdfunding an emerging area of research. A number of studies has been conducted on the business, marketing and sociotechnical aspects of crowdfunding campaigns. Examples include prediction of funding success (Greenberg *et al.* 2013; Koch & Siering 2015; Zhou *et al.* 2015), economics and regulatory aspects (Agrawal, Catalini & Goldfarb 2013; Moritz & Block 2016) and the culture of participation (Bannerman 2013; Gerber & Hui 2013). Meeting the initial funding goals in crowdfunding has been of particular interest and several indicators that have an effect on campaign quality have been identified. These include effective narratives containing trustworthy claims and intrinsic reasoning (Herzenstein, Sonenshein & Dholakia 2011), gender of the campaign initiators (Marom, Robb & Sade 2016), internal social capital accumulated at the crowdfunding platform (Colombo, Franzoni & Rossi-Lamastra 2015), continuous and effective communication through campaign updates during the funding period (Xu *et al.* 2014) and the effective use of social media platforms for directed marketing (Gerber, Hui & Kuo 2012; Etter, Grossglauser & Thiran 2013; Zheng *et al.* 2014).

What these examples have in common is the focus on, or approach to, crowdfunding as a study of the campaign initiators' ability to successfully achieve campaign funding goals. This is also well-founded as the success rates for the campaigns are rather low (20% in the technology category at Kickstarter.com) and crowdfunding projects generally either succeed



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

by narrow margins or else significantly fall behind their funding targets (Kickstarter.com 2016). Consequently, most of the active research on crowdfunding deals with understanding, defining and predicting characteristics that are associated with obtaining successful campaign funding. This basis does, however, also introduce the question of what success actually is and how it has been defined in existing crowdfunding research. Mollick reports that 59% of the campaign initiators on Kickstarter would like to establish a lasting venture through their campaigns (Mollick & Kuppuswamy 2014). The milestone to successfully fund the campaign is obviously important in this process. However, the ability to attract funding only reflects in very general terms a perspective on the prospects of continued success after the campaign. Continuing success relies on the initiators' ability to deliver products in a timely manner to backers, that represent the features and quality that were announced during the campaign. This ability is closely coupled with product development activities following the funding phase.

### 1.4. Motivation for this research

While the above-mentioned studies contribute to the understanding of different aspects of the crowdfunding paradigm, only a little is known about the performance of the campaigns in terms of their product development process and long term ability to succeed. Among different focuses that could be applied to study success, the aim of this study is to explore and investigate engineering design and product development challenges and issues that can hinder the long term success of reward-based crowdfunding campaigns. Accurate reporting's of such challenges and issues can help researchers and practitioners to better understand reward-based crowdfunding and particular characteristics that distinguishes the paradigm from other development approaches. Also, they can serve as probes for further research aiming to further investigate the topic.

The crowdfunding campaign 'Miito' is a recent case that illustrates some of the potential challenges associated with crowdfunded product development (Figure 2). Miito is a 'sustainable' alternative to the electric kettle, designed to heat water directly in a vessel using inductive heating, while trying to minimize excess water and energy usage. It was designed by a team of formally educated engineers and designers, and the team had shown working prototypes that were described in detail in the campaign material. Significantly exceeding the initial campaign funding goal, Miito received a lot of public and media attention and the project team collected €818,098 from 6052 backers. After several delays (the first shipments of the product were promised for April 2016), in March 2017 the campaign team announced the halt of the project due to loss of manufacturing partner, issues with certification and increased timeline and costs.

The case of Miito is not a unique example. As crowdfunding attracts the interest of the general public, challenges in crowdfunded product development have been covered by the media, and the main reasons for delays are listed as startling success (complexities of scale), manufacturing problems, the complexity of shipping and fulfilment, changes in project scope and unanticipated legal and regulatory (certification) issues (Pepitone 2012). Correspondingly, Mollick reports that over 75% of campaigns on Kickstarter could not deliver promised rewards to backers on time (Mollick 2014), and 9% of campaigns are canceled (Mollick 2015).



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

**Figure 2.** Miito is a 'sustainable' alternative to the electric kettle. It was designed by a team of engineers and designers; the team demonstrated working prototypes in their campaign material, and presented a detailed plan for development and manufacturing. In March 2017, the campaign team announced the halt of the project due to product development challenges (Picture from campaign at Kickstarter.com).

The work presented in this paper differs from the previous work presented above in three aspects. First, this study is focused on the product development process preceding the campaign funding period. Second, we quantitatively assess and report on the challenges that can be identified in the product development process for the studied campaigns. Third, we evaluate the campaign outcomes, in terms of products delivered to the campaign backers.

In this section we have introduced the current state of crowdfunding research. The rest of the paper is organized as follows. The next section describes our research methods and describes the development and use of the FMM. Next, we present our findings and discuss how delays are often related to the campaign initiators facing multifaceted challenges in the product development process. Finally, we conclude the paper with reflections on the results presented and their relation to design science. This includes perspectives on crowdfunding in relation to more conventional funding schemes and development activities.

## 2. Methods

As noted, our study is based on data collected from 144 reward-based crowdfunded product development campaigns that ran on Kickstarter.com. To analyze outcomes of these campaigns in a systematic fashion, we first developed and fine-tuned a failure mode model (FMM) through analysis of 30 campaigns, and then used the model to benchmark 114 campaigns, as outlined in Figure 3. The following sections describe the data, the pre-study that led to the FMM and the analysis of the dataset.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

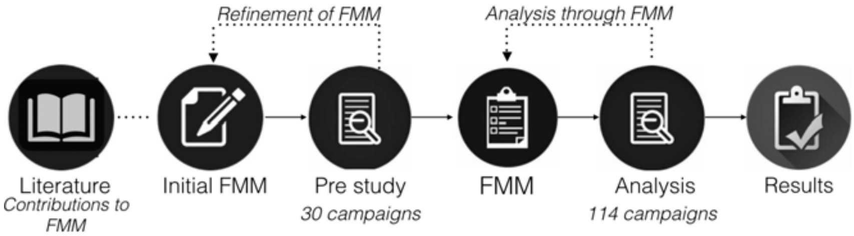



**Figure 3.** The workflow of the study. The process started with the initial failure mode model (FMM), which was compiled from the literature and refined through the pre-study. The final FMM was used as an assessment tool throughout the analysis, which included individual assessment of the original campaign material, campaign updates after funding and comments of the backers.

## 2.1. Crowdfunding on Kickstarter

Kickstarter was chosen for this study as it has been characterized as the largest and most dominant crowdfunding platform (Mollick 2014). To study one platform is an obvious limitation for generalizability regarding crowdfunding as a paradigm. It has, however, been argued that Kickstarter can 'serve as a broadly useful model for examining crowdfunding efforts' (Mollick 2014). At Kickstarter, the first milestone of a campaign is to reach a funding threshold by offering rewards to backers. Campaigns get funded and the backers are charged for their pledges only if the campaign reaches or exceeds the funding threshold. After payment processing fees and Kickstarter's mediation fee, 90–92% of the funds become available to the campaign initiators, who have the obligation to finalize development, manufacture the products and deliver them as rewards to campaign backers.

### *2.1.1. Inclusion criteria of the study*

Among various types of products, services and creative arts projects that seek funding on Kickstarter, our study only focused on crowdfunded product development campaigns that were successfully funded, and aimed to reward their backers with physical consumer technology products. Furthermore, we limit our dataset based on the following considerations:

(1) The campaign should fulfil the definition of reward-based crowdfunding (Massolution 2012) and offer preorders of a product.
(2) Campaigns should be listed in the Technology category ('Technology' and its subcategories: gadgets, sound and wearables).
(3) Campaigns must have had a funding goal above $5000 to substantiate some level of design complexity for the campaign initiators.
(4) Campaigns should aim to develop consumer products, therefore do-it-yourself (DIY) focused projects. such as printed circuit boards, fabrication tools and sub-assemblies were excluded from the study.
(5) Campaigns must have ended before August 1, 2015, to ensure enough lead time (2 years) for project creators to have shipped products to their backers by the time the study was conducted.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

(6) We study the campaign initiators' ability to deliver the products that the campaign concerns, excluding the 'token of appreciation' type rewards such as thank you cards or promotional t-shirts.

The initial dataset was extracted from the Kickstarter site, using a Python based web crawler. The data analysis was conducted by evaluating both the extracted data and through analysis directly on the Kickstarter site. The extracted data allowed for a comparative overview of descriptive campaign data, whereas the online analysis ensured media richness in terms of e.g. pictures not collected by the web crawler.

There were 325 campaigns, meeting the criteria above, launched over a two-year period (2013–2015). From this pool, 30 campaigns were selected for the pre-study of the failure modes and 114 additional campaigns were randomly selected for the main analysis. The 30 campaigns from the pre-study are not included in the analysis presented throughout the paper. The authors stopped the main analysis at 114 campaigns as they meet saturation in comprehending the patterns of the campaigns. Saturation in data analysis occurs once there is no additional emerging observation from the concurrent data analysis. It was further evaluated that the collected dataset was sufficient to perform overall statistical analysis.

## 2.2. Failure mode model

One of the main objectives of our study is to explore and understand the product development challenges in crowdfunding. Part of this process includes to establish an overview of what can go wrong after a crowdfunding campaign is successfully funded, and why campaigns might fail to deliver on promises. As the amount of data to be analyzed is substantial, we adopted failure mode analysis as a tool to systematize the process and developed a FMM, which can be seen in Table 2.

When assessing the FMM, note that incidents in Category 1 build primarily on feedback by backers. Incidents registered in Category 2 relate primarily to updates by the campaign initiators. A description of all failure modes is found in the middle column, and the number of campaigns to which each mode applies is given in the third column.

Failure mode analysis is widely used and practiced in engineering design and product development disciplines (Shimizu, Imagawa & Noguchi 2003; Stamatis 2003; Walsh, Dong & Tumer 2018), and a number of failure mode analysis frameworks exists. The thematic variation in the Kickstarter campaigns, and the characteristic documentation of crowdfunding campaigns, demand a less exhaustive and more broadly applicable tool. In this regard, the initial FMM borrows elements from tools, benchmarks and frameworks that address both generic product development issues and issues that are specific to crowdfunding.

The 'real-win-worth' RWW framework has been previously used to develop crowdfunding design guidelines by (Song *et al.* 2015*a*) and to evaluate risks in crowdfunding campaigns by (Song *et al.* 2015*b*), and it contributes to the product review aspects of FMM. Similarly, FMM borrows from principles on design for manufacturing (Kuo, Huang & Zhang 2001) to identify manufacturability issues of crowdfunded products. Economics and project management related aspects of product development are borrowed from Ulrich (2007) and guidelines published by two technical consultancy companies specialized in hardware



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

**Table 1.** Overview of the data corpus. 30 campaigns were included in the pre-study and 114 in the analysis presented. Of these, 69 has delivered products to their backers. Out of the 45 campaigns that has not yet delivered, 30 are still active. 15 campaigns are stalled being either officially left behind or lacking response from creators

| **Campaign overview:** | ***Campaigns*** |
|---|---|
| Campaigns reviewed for the pre-study | 30 |
| Campaigns reviewed for the analysis | *114* |
| ***Campaigns that delivered products:*** | ***69*** |
| (i) Delivered in time (less than 3 months' delay) | 36 |
| (ii) Delivered with 3–12 months' delay | 28 |
| (iii) Delivered with >12 months' delay | 5 |
| ***Campaigns have not delivered:*** | ***45*** |
| (iv) >12 months delayed but still active | 30 |
| (v) Stalled or abandoned campaigns | *15* |

entrepreneurship helped identity failure modes related to component sourcing and product certifications. (Einstein 2015*a*,*b*; Dragon Innovation 2016).

Based on these benchmarks, guidelines and models, an initial list of 53 metrics and failure modes were compiled. During the pre-study, a subset of crowdfunding campaigns from Kickstarter was analyzed in depth, with the aim of mapping the identified issues to the initial list and reducing its dimensionality through empirical analysis. In total, 20 failure modes were identified to be relevant from the initial list for the initial 30 projects studied. The process of reducing the dimensionality of the FMM took place as a collaborative process between the authors and the majority of the initial metrics were incorporated. This was made possible by identifying and scoping the appropriate taxon's. The failure mode 'certification issues' were e.g. derived through the merger of more specific initial metrics 'FCC certification issues' and 'CE certification issues'.

FMM distinguishes the types of issues based on the source of the data. The first category is primarily based on the backers' feedback and it reveals whether the delivered products lack any features or live up to the expectations of the backers. The second category is primarily based on the campaign descriptions and updates provided by the campaign initiators, and shows issues related to design, manufacturing, project management and operations. In many cases it was also possible to triangulate the source data as presented in Section 2.4. It should be noted that product related issues such as features, functionality and quality can only be analyzed for the campaigns that have delivered products but process related issues were collected from all campaigns, including those that are yet to ship after more than 12 months of delays. Table 1 presents an overview of the whole data corpus. Of the 114 campaigns that were studied, 69 delivered products to their backers. Out of the 45 campaigns that had delivered by August 1st 2017, 30 were still active. 15 campaigns were stalled being either officially left behind or lacking response from creators.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

### 2.3. Promises and failure

In reward-based crowdfunding, the campaign initiators primarily make two types of promises to their backers. These concern (i) a date of delivery and (ii) a set of specific features, functionality and quality attributes of the product that are presented during the campaign. Consequently, our analysis concerns with two types of *failures* – failure to deliver a product that has the features, functionality or quality that has been promised during the campaign and failure to deliver in a reasonable time.

Delays for launching new products are not unique to crowdfunded products and a 3-month delay has been suggested as acceptable when defining 'timeliness' (Bayus, Jain & Rao 2001). This concretely means that our analysis regards products delivered within less than 3 months of the announced deadline as delivered on time.

### 2.4. Campaign review process

While using the FMM as an assessment scorecard, two coders were involved in the process of aggregating and analyzing data from the campaigns. An example of the campaign layout is presented in Figure 4. Note how, besides the campaign status in terms of funding, video and written background material, the presentation also features different tabs with updates from the campaign initiators and comments from backers. In the right part of the figure a sample of comments is shown. Where Figure 3 illustrates the workflow for the evaluation of campaign content for each project included in the study. The following parts of the campaign content were included in the analysis:

*Campaign description page.* Campaigns typically contain a short 'marketing' video, followed by an article that provides information on various aspects of the project. This includes an overall description of the product, delivery timeline, project plan, reflections about risk and challenges and, in some cases, a presentation of the project team. The campaign also introduces the different rewards offered to backers. This content was evaluated and descriptive campaign data was collected to establish foundational knowledge on every campaign prior to the analysis of potential failure modes. In addition, campaign dates, duration, funding obtained and the number of backers were recorded.

*Comments.* Backers can post comments during various stages of the campaign. This is considered to be one of the strong points of crowdfunded product development, as the backers can provide continuous feedback and constructive criticism during the development process of the projects (Anderson & Simester 2014). Campaign initiators can reply to the comments and eventually an active dialogue may take place. Whenever replies from campaign initiators were available they were included in the analysis, as part of the specific comment. To accommodate that single complains by backers are not necessarily representative, a specific topic needed to be addressed in $\geqslant 2$ of the studied comments before it was registered in the FMM.

Our pre-study showed that the nature of the comments can be mapped to four phases of a typical campaign – (i) funding period, (ii) product development, (iii) shipping and backers first impressions and (iv) product reviews. Projects can gather thousands of comments of varying lengths. To make the analysis feasible,



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

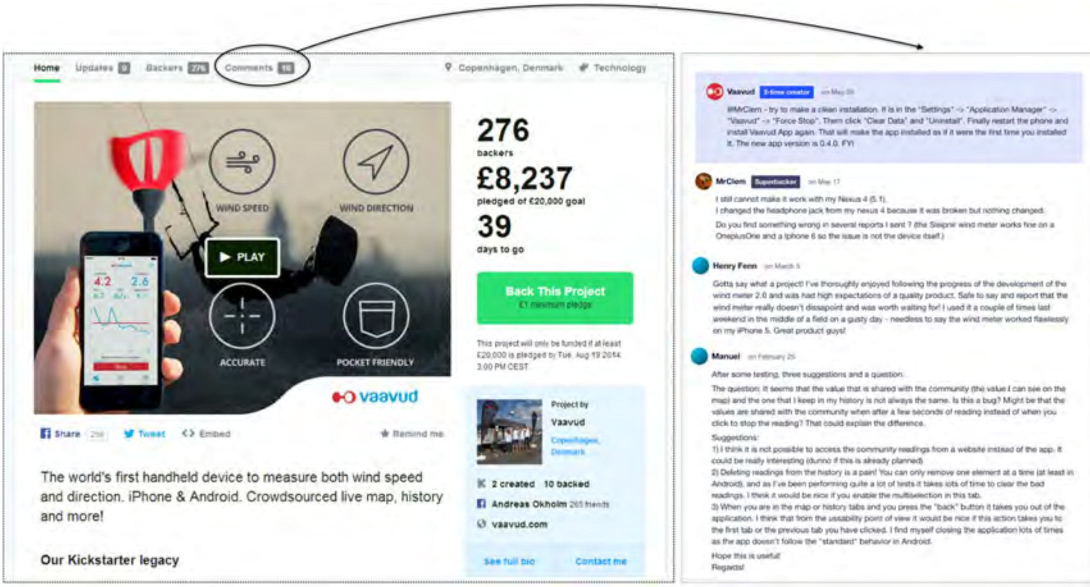



**Figure 4.** Example from the Vaavud Wind Meter campaign at Kickstarter.com. Note how the campaign besides the campaign status in terms of funding, campaign video and written background material also features different tabs with updates from the campaign initiators and comments from backers. In the right part of the figure a sample of comments are shown.

we have randomly chosen 40 comments – 10 comments that have at least 140 characters – from each of the 4 categories – for each campaign. Descriptive campaign characteristics (e.g. the end of the funding period) were used to identify the date for the specific phases introduced above and the web crawler carried out the random selection of comments. For significantly delayed campaigns, comments in the first two categories helped to clarify if the project was still active. For campaigns that have shipped rewards; the last two categories also provided insights for the FMM, in terms of assessing whether the product has lived up to the expectations of the backers.

*Updates by project initiators.* Campaign initiators can post updates on the progress of their campaigns to the campaign backers. Updates can vary from quick status updates to detailed statements on manufacturing challenges. Our analysis uses the updates to benchmark the projects against the FMM issues that are related to design, manufacturing, project management and operations.

Despite the variation in characteristics of these types of data, they allowed for triangulation during the analysis and coding process. This was possible as overlapping and mirrored content were often represented in e.g. both campaign updates and comments from the backers. Whenever possible, triangulation was conducted to increase the validity and robustness of the analysis (Voss, Tsikriktsis & Frohlich 2002). In this way, the different sources of data allowed for a chain of evidence to be established. By following the process presented by (Partington 2000) incidents described directly in the data were coded into the categories of the FMM. From a comparison of each incident with previous incidents in the same



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

metrics of the FMM, the authors developed theoretical properties of each failure mode and the dimensions of each these modes.

### 2.5. Limitations of research methods

The basis for this study is the data that is available on Kickstarter. The project updates and descriptions are self-reported by the campaign initiators and therefore carry subjective bias – e.g. attributing delays to factors beyond their control when this might not be the case. While the backers' comments can counterbalance some of such issues, they can also introduce a cross-correlation bias – such as providing negative reviews for the quality of the product if it was delivered late. Finally, due to the qualitative nature of the updates and the comments in crowdfunding campaigns, there is the possibility of evaluator bias. Two independent coders with advanced degrees in engineering design analyzed the campaigns presented in the study. Owing to the substantial amount of data collected for the analysis, the coders worked collaboratively. During the process the coders compared and discussed their assessments and only a few discrepancies were encountered. In such cases, further dialogue on the interpretations of the data resulted in mutual compliance in all cases. The collaborative nature of the approach in which the coders compared and discussed their assessments did not make it possible to estimate a measure of inter-rater reliability.

## 3. Results

In this section we present the result of our analysis. The motivation behind this study was exploratory, and our results identify and quantify issues that occur during the product development process, and also issues regarding the delivered products reported by the backers. The overall results of the analysis are presented in Table 2, which presents the final FMM and an overview of the results. This section provides further details in the light of the research questions presented in Section 1.

### 3.1. Do campaigns deliver on their promises?

Our analysis is based on the assessment of two basic promises of a typical crowdfunding campaign: delivering a functional product to all backers, with the features and quality that were advertised during the campaign period, and delivering it on time. These promises are not mutually exclusive; while some campaigns might deliver inferior products on time, others might be severely delayed but deliver a full set of promised features. In either case, *failures* in terms of product functionality and/or delays can be considered as the consequences of the underlying failure modes identified in the FFM. In the following section we outline the performance of the campaigns included in this study in terms of their timeliness.

#### *3.1.1. Campaign delays*

Figure 5 summarizes the campaign initiators' ability to deliver products in time: 28 campaigns (32%) delivered rewards within the timeframe they had initially promised to their backers, 36 (25%) of the campaigns were delivered with 3–12 months' delays whereas 50 (43%) of the campaigns exceeded one full year in



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

Table 2. The failure mode model. Incidents in Category 1 builds primarily on feedback by backers. Incidents registered in Category 2 relates primarily to updates by the campaign initiators. A description of all failure modes is found in the middle column

| Failure modes | Description | Number of campaigns |
|---|---|---|
| **Category 1: Backer feedback** | **Only applies to campaigns that have delivered the promised rewards to all backers (69).* | — |
| **Features** | — | — |
| 1. Product reported to lack feature(s) | Backers report expected feature(s) to be lacking – features includes the products distinguishing characteristics being central to 'what it does' | 17 |
| **Functionality & quality** | — | — |
| 2. Build quality not meeting expectations | Backers report disappointment in build quality – finish, materials and parts – of product. | 17 |
| 3. One or more design flaws | Backers report that product has design flaw(s) that hinders core functionality. | 15 |
| 4. Usability not meeting expectations | Backers report usability to not meet expectations and hinders elegance and clarity of interaction. Incl. software | 12 |
| **Category 2: Product Development Process** | *Applies to all campaigns whether rewards are delivered or not (114)* | — |
| **Design & Manufacture** | — | — |
| 5. Manufacturing quality issues | Campaign updates document quality issues related to design or manufacturing processes. | 32 |
| 6. Manufacturing costs too high | Campaign updates document that manufacturing cost lead to delay. | 2 |
| 7. Component sourcing issues | Campaign updates document that team face complications in sourcing components or parts. | 16 |
| 8. Certification delays project | Campaign updates document that product is delayed due to challenges in obtaining product certifications. | 5 |
| 9. Complexity of scale | Campaign updates document that high interest in the campaign led to scalability complexity. | 5 |
| 10. Packaging/ Assembly issues | Campaign updates document issues in product assembly process or packaging. | 4 |
| 11. Design for manufacturing deficiencies | Campaign updates document that team struggles to mature design beyond 'proof of concept' stage. | 12 |
| 12. Quality control complications | Campaign updates document that team is challenged in handling the CQ in the manufacturing process. | 3 |
| 13. Consultancy or partner deadlines not met | Campaign updates document that the development process is delayed by external collaboration partners not meeting deadlines. | 5 |



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

Table 2. (continued)

| | | |
|---|---|---|
| **Management & Operations** | — | — |
| 14. Team report: campaign not economically viable | Campaign updates document that delivery of rewards will be made with either 0 profit margin or a loss. | 4 |
| 15. Management challenges | Campaign updates document that team have been challenged in administration of own organization and establishing realistic project schedule. | 11 |
| 16. Shipping/ fulfilment issues | Campaign updates document that team struggles in handling shipping and fulfilment. | 7 |
| 17. Customs issues | Campaign updates document that customs and administrative documentation have not been planned for and handled accordingly. | 6 |
| 18. Legal issues (IP) | Campaign updates document that campaign is facing IP violation issues related to their product. | 2 |
| 19. Team lost faith in project | Campaign updates document that team has lost faith in the product and will not complete the campaign. | 3 |
| 20. The team went underground | Campaign updates document that the team has not provided updates or responded to queries for several months. | 12 |

delay. In this group, exceeding 12 months of delay, 30 (26%) of the campaigns had not yet delivered any products. 15 (13%) of the campaigns were stalled, being either officially left behind or lacking response from creators. Only 5 (4%) of the campaigns delivered products after a delay exceeding 12 months.

At the time of the analysis, 26% of the campaigns were still striving for delivering the products despite a +12 months' delay. Given the fact that only 4% of the campaigns in the study managed to deliver after +12 months' delays, it is remains uncertain whether these campaigns will eventually deliver.

This general distribution tells us that delays are not uncommon for reward-based crowdfunding campaigns. More than half of the campaigns have nevertheless been able to deliver their products within a year after the initial deadline. In spite of significant delays, the majority of the campaigns which had not yet delivered their products (30 campaigns, 26%) were still actively engaged in the development of their products. There are, however, no guaranties that the campaign initiators will eventually be able to deliver despite their continued efforts.

In a study by Mollick it was found that 75,1% of crowdfunding campaigns did not deliver reward in time and 33% had yet to deliver after 8 months' delay (Mollick 2014). These findings slightly vary from our results, and it is our assumption that the variation is primarily related to variation in the categories of campaigns included in the study.

#### *3.1.2. Product features*

The majority of campaign backers not only expect to have the products delivered on time. They also expect products to be functional and to possess the features that



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

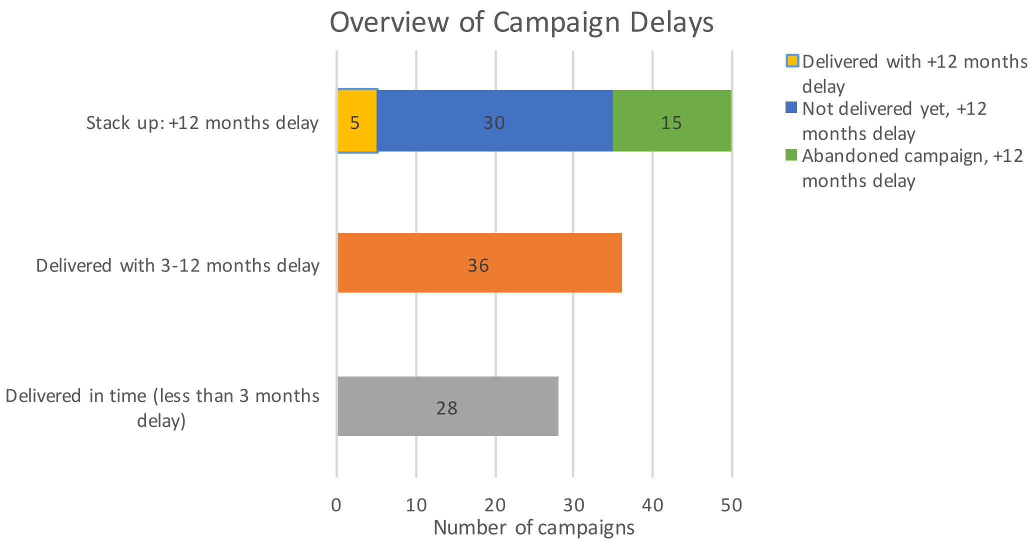



**Figure 5.** Overview of the campaigns ability to deliver products to campaigns backers. The legends to the left presents an overall categorization of campaigns in terms of product delivery. The legends to the right represents the three color codes in the stack-up of campaigns delayed by more than 12 months.

were advertised during the funding phase of the campaign. Out of 114 campaigns analyzed, 69 of them had delivered products, as presented in Table 1 and Figure 5. Through the analysis, we identified that 17 of these products (25%) were reported to lack one or more features. Figure 6 illustrates the association between campaign delays and the reported lack of product features. The figure presents that delayed campaigns are significantly more likely to deliver products that are reported to be missing one or more of the promised features ($p = 0.030$, $CI = 0.95$ by Chi-square test).

Despite the significant increase in reports of missing features, the majority of products are still reported to meet the backers' expectations. This result does, however, indicate that, when campaigns do not deliver products on time, there is an increased risk that the product will not meet expectations in terms of features. In the later discussion we reflect on potential causes behind this distribution.

#### 3.1.3. *Functionality & quality*

The third aspect that affects the overall satisfaction of the backers is the quality and the functionality of the delivered products. The FMM has three attributes that are concerned with functionality and quality, all based on feedback provided by the backers through comments: build quality, design flaws and usability. Build quality refers to backer's assessment of product finish, quality of materials and parts used. An example is the 'The Flare Audio' campaign, which developed a set of headphones where backers quickly started to complain about the build quality of the product. In particular, the cables seemed to fail from unexpectedly early fatigue resulting in faulty products.

Design flaws refer to specific flaws in the design, which backers report as a hindrance for use. For instance, the 'Thermodo' campaign delivered a tiny digital thermometer which can be connected to a smartphone though the headphone



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

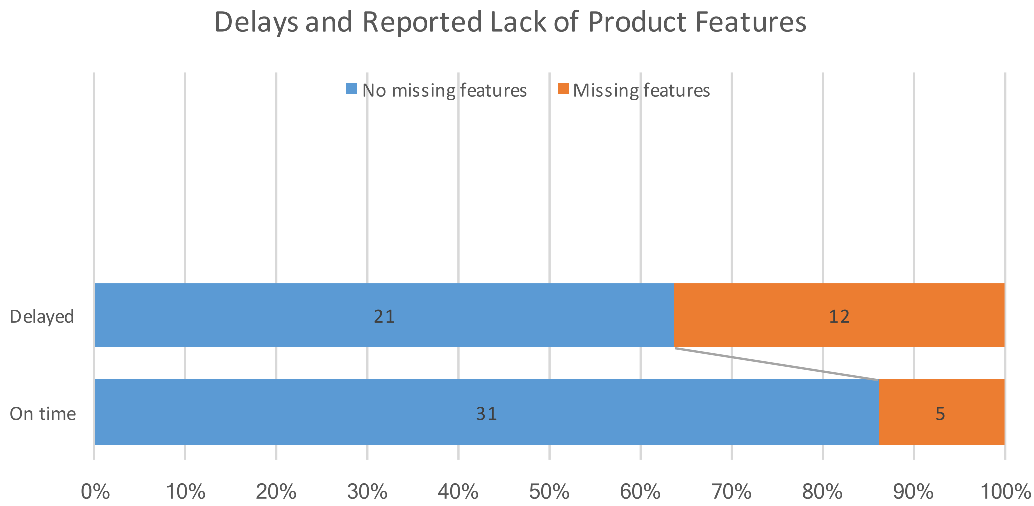



**Figure 6.** Representation of reported lack of product features for campaigns that delivered products on time and delayed product delivery. Delayed products were reported to lack features significantly more often. Note that the $x$-axis represents the percentage of campaigns.

jack port, and when not in use, the product is intended to be stored in a keyring. Through the comments section of the campaign, it is discovered that many backers had lost the Thermodo from their keyring, as the keyring slot randomly ejected the Thermodo.

Usability refers to the elegance and the clarity of interaction with the product, which also includes dedicated software and apps for the shipped products in the situations where applicable. Such issues were reported for the Flyshark campaign, which delivered a foldable and portable wireless keyboard. Usability issues were reported regarding the folding mechanism, which was not designed to allow the use of the keyboard on uneven surfaces.

These different functionality and quality issues are not mutually exclusive, and some products might suffer from multiple issues at the same time. Our analysis revealed that 39 campaigns (out of 69 that delivered products) were identified to have 53 quality and functionality issues ($\sim$1, 4 issues per product). Figure 7 illustrates how these issues were distributed among campaigns that were respectively delayed or delivered on time.

What can be observed from the results in Figure 7 is that the usability issues are significantly increased for the products delivered by delayed campaigns ($p = 0.038$, $CI = 0.95$). The presence of design flaws was also increasingly reported for delayed products, but not significantly. The results also show that campaign delays do not seem to change the variation in reported product build quality issues. Once again, the results indicate that when campaigns are delayed there is an increased probability that the delivered product will not meet functionality and quality expectations. We present further reflections on this topic in the later discussion.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

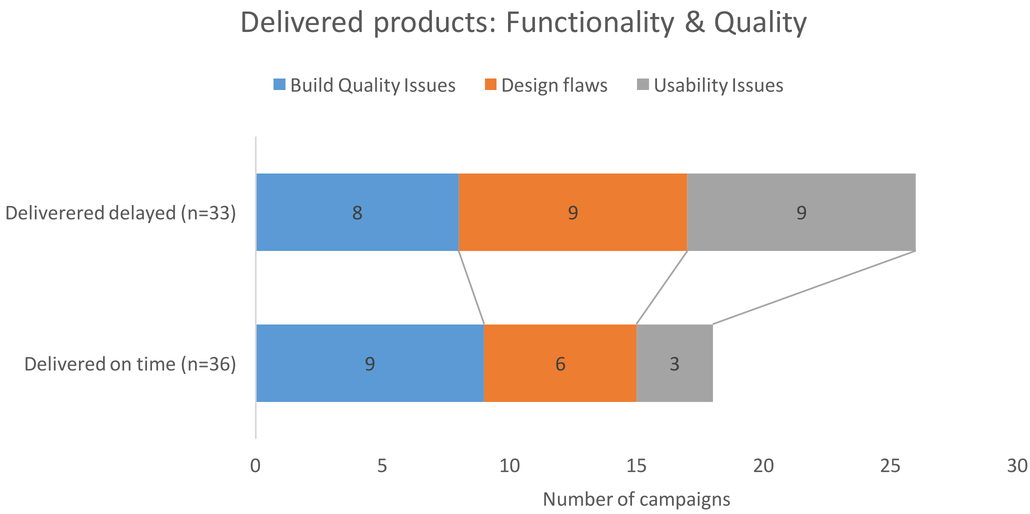



**Figure 7.** Representation of reported build quality issues, design flaws and usability issues for products delivered in time and delayed delivery of products. The results present that design flaws and usability issues were increasingly reported for delayed products, whereas build quality issues did not increase. Note that the $x$-axis represents the number of campaigns.

## 3.2. Challenges in product development

Campaign updates are an essential part of crowdfunding campaigns, where campaign initiators inform and include their backers in the product development through detailed posts (Yancey 2016). An example of an update, originally from the campaign named 'Opløft' (Kickstarter 2016), is presented in Figure 8. Combined with the responses to backer questions and comments, campaign updates provide rich information on the challenges that are faced in the various stages of development, manufacturing and fulfilment of the campaign.

The second part of the FMM analysis is concerned with design, manufacturing, operations and project management issues that have been reported through these updates. Unlike the first part of the analysis, which deals with campaigns that have delivered products (69); the second part of the FMM concerns all campaigns (114). In total 129 incidents were recorded in the FMM, corresponding to 1, 13 incidents per campaign.

### 3.2.1. *Design and manufacture*

The Design and Manufacture category of the FMM contains nine different failure modes. As it is presented in the Table 2 and Figure 9, three of these stand out among others in terms of their recorded occurrences. These are: (i) manufacturing quality issues (ii) component sourcing issues (iii) design for manufacturing deficiencies.

'Manufacturing quality issues' refers to two typical cases that are often correlated and hard to separate from each other. In some situations, the selected manufacturing process or technology does not live up to the expectations of the campaign initiators. In other cases, the design of the product does not fit the selected manufacturing processes. 'Component sourcing issues' refers to the situation where the demands for specific components and materials cannot be



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

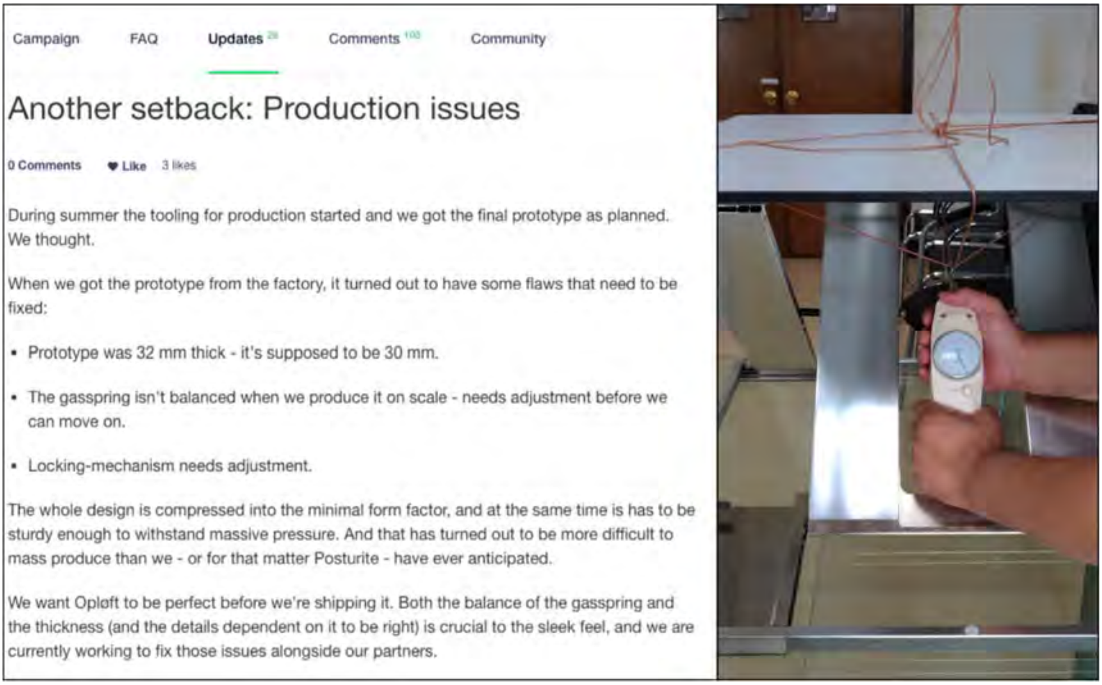



**Figure 8.** Example of a campaign update. Updates communicate the progress of the campaign to their backers. Projects that are delayed or undergoing significant design changes often provide updates that detail reasoning behind the delays or design changes. We have extracted information from campaign updates to assess the reported issues regarding design, manufacturing, operations and management.

met by the suppliers due to cost, trends, global demands or the scale of the production. Finally, 'Design for Manufacturing' deficiencies describe cases where the campaign initiators are not capable of elevating the design of the prototypes beyond a 'proof of concept' stage prior to engaging with manufacturing partners.

Figure 9 further illustrates the interplay between these categories and the campaign delays. Generally, campaigns that have not delivered products face multifaceted challenges compared to the campaigns that were delivered on time.

This finding provides indications that manufacturing quality issues could be one of the main challenges hindering initiators from delivering rewards to the backers. An interpretation of the results can also be that campaigns facing delays are challenged by component sourcing issues and DfM deficiencies due to a lack of adequate manufacturing-oriented product development insights prior to launching the campaign. While product development is multidimensional, one integrating activity to accommodate such challenges is rigorous and adequate prototyping activities throughput the design process.

#### *3.2.2. Management & Operations*

The final subcategory of the FMM describes management and operations related issues that the campaigns encountered. The three most common issues are related to (i) management challenges, (ii) shipping & fulfilment problems and issues regarding (iii) customs. Figure 10 illustrates the distribution of these issues in relation to campaign delays. Management challenges were



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

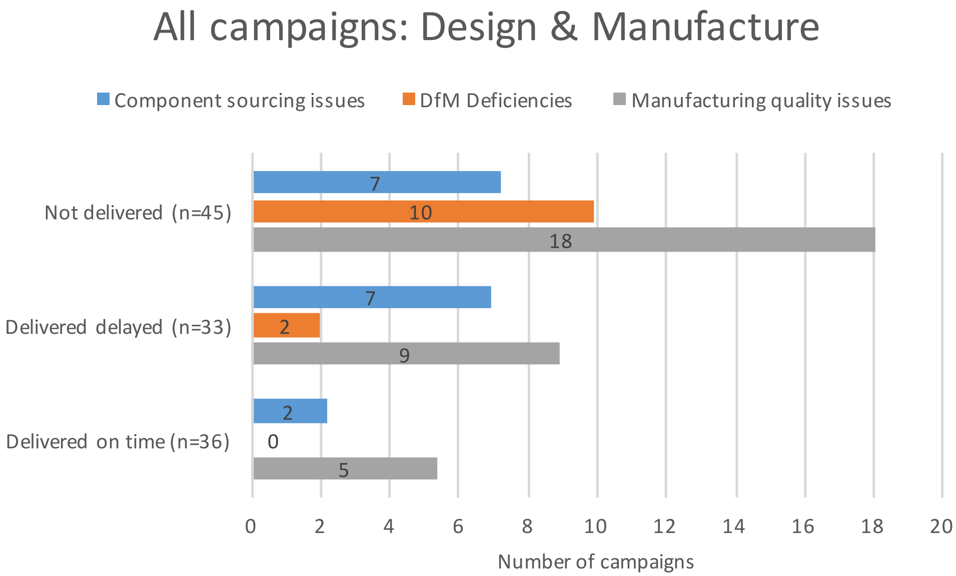



**Figure 9.** Representation of the top three failure modes recorded under the design and manufacture heading. The results are presented in three categories according to their timeliness. Delivered on time, delivered delayed and not delivered. It is seen how the recorded challenges overall are increasing along with increased delay. Note that the $x$-axis represents the number of campaigns.

reported for 11 campaigns. This concerns situations where initiators described challenges related to administration of their own organization, their coordination of resources and establishment of realistic schedules for the projects. The campaigns which delivered products on time stand out by not reporting management challenges as a hindrance for the project. Management challenges were significantly over-represented ($p = 0.033$, $CI = 0.95$, by Chi-square test) among the projects which have not yet delivered products (8 campaigns). Shipping & fulfilment (7 campaigns) and 'customers' (6 campaigns) were only reported for the campaigns that have delivered products. A general observation for these challenges were their 'unforeseen' characteristics; as they were reported as to be first-time experiences, and described as being surprisingly demanding.

## 4. Discussion

In this section we present a discussion of our results in the light of our research questions. We further reflect on how our results contribute to our understanding of crowdfunding and crowdfunded product development in the perspective of design science. This includes our perspective on crowdfunding in relation to more conventional funding schemes and development activities. Finally, we outline opportunities for further work.

### 4.1. Contribution of this work

We consider the findings of this study exploratory, and the main contribution being the identification and quantification of product development challenges that crowdfunding campaigns encounter after the campaign funding period.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

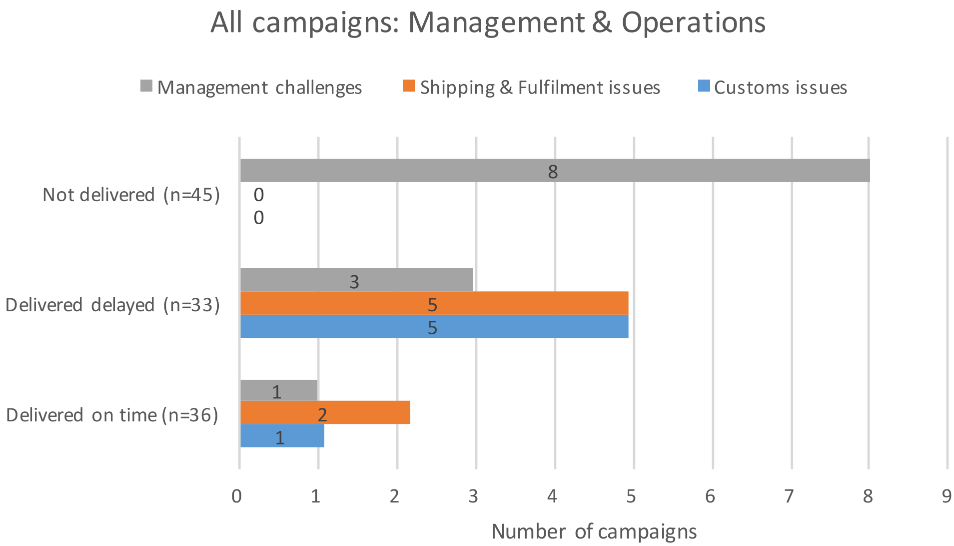



**Figure 10.** Representation of the top three failure modes on management and operations. The results are presented in three categories according to their timeliness. Management challenges were significantly more often reported among the campaigns that did not yet deliver products. Whereas only few incidents (4) were recorded for the campaigns that delivered in time. In total 13 incidents were recorded for the campaigns that delivered delayed. Note that the $x$-axis represents the number of campaigns.

Further we deliver an identification and quantification of failures to meet promises on the quality and functionality of the delivered products. Due to the exploratory nature of the study we refrain from formally verifying specific hypotheses. Crowdfunding is an evolving topic and we find this approach appropriate, as little prior work exists to guide our study. We expect that our findings will be useful for future theory building and design support tools dedicated to crowdfunded product development. We further find that the insights delivered can be of value to practitioners with interest in the dynamics of the topic.

#### *4.1.1. What does the results of this study tell?*

The objective of this study was to explore and understand why some reward-based crowdfunding campaigns fail in delivering on their promises, and how backers evaluate the products shipped to them as rewards, in terms of expected features and quality.

In order to investigate these topics, we established two aspects that can characterize 'failure' of the campaign. The campaigns can fail in the parameter of timelines; the ability to deliver the promised rewards to backers within a reasonable timeframe of the initial announced deadline. Also, the campaigns can fail by not delivering a product that has the features, functionality or quality that was promised in the campaign material.

Our analysis shows that both aspects of failure described in this study are common. Only 36 of 114 the campaigns in our dataset delivered products in a timely manner. Among the 69 campaigns managed to deliver products (timely or not) 30 of them were not lacking functionality and quality attributes that were expected by the backers during the funding phase. These findings have been



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

highlighted through the FMM presented in Table 2 and the graphs presented in Section 3.2 'Product development challenges'.

Our study also shows how 50 (43%) of the campaigns are delayed by more than 12 months. As presented in Section 1.2, the objective for the majority of campaign initiators is to start a lasting venture (Mollick & Kuppuswamy 2014) and in this light it is most likely unsatisfactory for these creators to face long delays for their campaigns. It has previously been documented in research how companies suffer significant market evaluation penalties when announcing delays of announced new products (Hendricks & Singhal 1997). Hereby we infer that; delays cause negative business effects for the campaign creators' long term success and the campaign creators could most likely benefit from dedicated support tools to increase the likelihood of accommodating the different challenges outlined in this study.

When evaluating how campaign backers evaluate rewards in terms of expected product features and quality, we find that 17 (∼25%) of the delivered products are overall reported to lack expected features. Further, it is shown that product features will be significantly more likely to be lacking if the campaign is delayed more than 3 months. A similar significant result is reported for the products' usability, 12 campaigns (∼17%), also follows the patterns that delayed campaigns are less likely to live up to the expectations of the backers. The product build quality however did not follow the pattern introduced above and was evaluated evenly by the backers across the different categories of timeliness. One explanation describing the result can be a variance in the backer's preferences or evaluation of product quality that we do currently not understand.

Manufacturing quality issues were the most frequently occurring failure mode in the analysis. Further investigation of the correlation between 'functionality and quality' and 'design and manufacture' aspects of the FMM show that 30 (∼43%) of the campaigns that delivered products with missing features also faced manufacturing quality issues, and build quality issues were reported for 43 (∼64%) of the campaigns with manufacturing quality issues. This indicates that manufacturing quality issues can lead to tradeoffs that compromise the promises that are made to backers in terms of product attributes.

Another ambition of this study was to investigate if particular product development issues could be identified as primary causes of failure. Through our analysis we have identified that five failure modes were significantly more often reported for campaigns which have been delayed or not yet delivered products to their backers. These are:

(1) Reported lack of expected features.
(2) Reported usability issues.
(3) Design for Manufacturing deficiencies.
(4) Manufacturing quality issues.
(5) Management challenges.

We find that these five failure modes should be highlighted as particular challenges in crowdfunded product development. This claim should though not be considered as an isolated measure and rather should be interpreted holistically. Despite the significance of their occurrence, the multifaceted characteristics of product development do not allow for a particular role in special campaigns or generalizations on their relevance. In this regard, we conclude that no single design



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

implication should be highlighted as the main cause for failure in crowdfunded product development.

## 4.2. Kickstarter as a moderating platform

A topic of ongoing debate concerns whether delays and disappointing campaign fulfilment can be associated with failure in crowdfunding (Yancey 2016). For this study, we establish our analysis and results from two types failure introduced in Section 2.3 and the FMM. Kickstarter ambassadors argue that crowdfunding should not be compared to a webshop or a normal hardware store. Ambassadors argue that uncertainty in the projects is high and delays should be expected. Essentially this discourse underlines that a focus on deadlines negatively incentivizes campaign initiators to take shortcuts in the product development process. Others argue that Kickstarter does not prioritize and enforce its responsibility to keep the campaign initiators responsible for promises made to their backers (Yancey 2016). In this sense, Kickstarter indemnifies the platform's responsibility and legal liability from the campaigns on the platform. As a digital and platform oriented business organization, Kickstarter is a child of the digital revolution. Despite rapid growth, the paradigm is potentially still in its infancy and our understanding of crowdfunding's effect on engineering design and product development is still limited. This includes the legislative aspects suitable for balancing the different interests and interactions of Kickstarter and similar platforms.

Various aspects of establishing and maintaining project plans have been a topic of substantial research in both engineering design and management literature. To meet product development and fulfilment requirements requires careful project planning (Ulrich 2007). We believe that this also applies to crowdfunding and it is the interest of all involved parties to establish a positive reputation around the crowdfunding paradigm. Rewards that do not meet the backer's expectations can cause bad publicity. Further, Kickstarter will be challenged on accountability as moderator and, finally, the campaign initiators must allocate additional project resources if they encounter unexpected causes of delay or design challenges. As discussed above such is not only a matter of spending additional resources but can also cause significant market evaluation penalties.

## 4.3. Are campaigns intensified to oversell concepts?

The dynamics of crowdfunding imply that successfully funding a campaign is the first important 'stop or go' milestone for campaign initiators. Such dynamics contain a paradox, which can be considered as a design implication of its own: It can be tempting for campaign initiators to 'oversell' the product to attract as much funding as possible. This, along with spending only minimal product development resources before knowing the campaign outcome – in the extreme, using crowdfunding for validating the market potential of early concept prototypes. Based on our results we hypnotize that the large number of functionality and quality issues for delayed campaigns can be related to this paradox.

Such issues are also acknowledged by some of the main actors in the crowdfunding community. A recent initiative have been launched by Kickstarter, the electronic component distributor Avnet, and the hardware consultancy firm



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

Dragon Innovation (Yulman *et al.* 2017). The initiative aims to support the creators in design and manufacturing before they launch their crowdfunding campaigns.

## 4.4. Reward-based crowdfunding versus conventional funding schemes and development processes

In this section we present some initial perspectives on how crowdfunded product development might differ from more conventional funding schemes and what affects the dynamics have on the product development process.

### *4.4.1. Product offerings and design*

As previously introduced, crowdfunding is essentially an open call through the internet. Backing a crowdfunding campaign can be a valuable social activity for the campaign backers (Belleflamme *et al.* 2014). Part of the backers commitment to the campaign is connected to expectations of an inclusive product development process. Such expectations set particular requirements for the openness of the product development approach and interactions between the backers and the developers. In this sense the (digital) user plays an increasingly important role in the way goods are used and consumed (Brenner *et al.* 2014), and these dynamics share some similarities with the 'open-design' paradigm (Boisseau, Omhover & Bouchard 2018), 'mass collaboration design' (Ball & Lewis 2018), 'social product development' (Forbes & Schaefer 2017) and the 'creative consumers' phenomenon by Berthon *et al.* (2007). Such requirements for openness can be considered a particular characteristic of crowdfunded product development.

As previously introduced, Mollick and Kuppuswamy identified that among the top motivations for campaign initiators to choose crowdfunding were: 'To see if there was demand for the project', and 'To connect directly with a community of fans or supporters'. (Mollick & Kuppuswamy 2014). Such motivations align well with an open approach to product development as introduced above. In a product development perspective, it might also be a challenge or a direct hindrance for success, as crowdfunding campaigns are not a direct substitute for practicing user oriented design or customer development. Feedback and collaboration with backers can though provide some similar insights. This occurs, however, at a point in time where the campaign initiators have simultaneously also started selling preorders of the product through the campaign. A potential result can be inertia created from changing product features, characteristics or business model after a large community of backers have made their contributions. With similar reflections, the US based hardware accelerator BOLT has made a critical argument toward user involvement aspects of crowdfunding (Einstein 2015*c*). In line with recognized entrepreneurship literature (Ries 2011; Blank 2012; Aulet 2013) entrepreneurs pursuing a crowdfunding campaign should in this perspective carry out a palette of development activities, and in particular make use of prototyping, prior to their campaign, to support them in identifying their initial 'beach-head market' and core product offerings, a similar fashion to entrepreneurs pursuing traditional sales channels.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

#### 4.4.2. Manufacturing for crowdfunding campaigns

A characteristic for all crowdfunding campaigns is that, prior to the campaign, the outcome is unknown. Thus it is not known how many units to manufacture or what kind of economic resources there will be to do so. This makes final decisions on suitable manufacturing processes or partners difficult, especially as the campaign outcome (essentially, working as a market validation of the product) can be used as leverage in negotiations for attractive contracts. Through the data collection of this study, we have encountered examples indicating that some campaign initiators will not engage in dialogue with potential manufacturing partners and suppliers until after the campaign has been finalized – this would be the case with the Miito campaign introduced earlier. To the best of our knowledge, comparative research, focused on entrepreneurs following conventional funding schemes, currently does not exist. However, as introduced in Section 4.3, an ecosystem focused on manufacturing and fulfilment has started to emerge around the crowdfunding paradigm, and the manufacturing ecosystem is currently undergoing change toward broader openness toward early stage start-up companies with a need for 'high mix low volume' manufacturing set-ups (Dragon Innovation 2016; Bolt 2017).

A general limitation in comparing crowdfunding with conventional funding schemes is that we cannot identify if the campaign initiators are also pursuing other funding sources. In our view, crowdfunding should not be seen as an either/or alternative to traditional venture capital. We hypothesize that it is relatively common for the campaign initiators to attract multiple sources of funding for their projects. However, campaign initiators are 'free' to utilize the funds collected from their crowdfunding campaign as they find most appropriate. This can be considered different from public support programs for entrepreneurship venture capital traded for equity.

### 4.5. Opportunities in research on crowdfunded product development

From conducting this research, a range of new hypotheses have been established and we see future research potential in crowdfunded product development. Crowdfunding platforms such as Kickstarter.com are rich data libraries of product development cases. Related research could be conducted to study such topics as the impact of early versus late design decisions in product development (Tan, Otto & Wood 2017). Another topic could be crowdfunding entrepreneurs' ability to work within what has been presented as the novelty 'sweet spot' of invention (He & Luo 2017). In the following sections we elaborate three topic proposals which could support future theory building from the results presented in this study.

#### 4.5.1. Long term performance

An obvious opportunity is to carry forward this study and evaluate how the campaign teams perform in the market outside the crowdfunding environment. Other studies have found that failure rates for 'new technology products' and 'consumer goods' are documented to be around 40%. Comparison with the crowdfunding environment is (due to the nature of crowdfunding) not directly applicable, but, when campaigns start marketing their products post



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

campaign, such comparisons becomes possible. Recently, the commercial giant Amazon started the initiative named Launchpad (Launchpad 2017). The initiative offers start-ups special vendor benefits and support in handling sales and distribution. Research questions to be studied are e.g. if crowdfunded products and organizations have a higher success rate in the market.

#### 4.5.2. Adaption of design research

The results of our study show how many crowdfunding campaigns struggle in meeting the promises made to their backers. While we have documented specific product development challenges some aspects of the product development process remain uncovered in this work. Throughout the past decades the engineering design community has proposed various design approaches and methodologies, with the aim to support designers by providing tools, methods and guidelines to improve the chances of producing successful products (Blessing, Chakrabarti & Wallace 1998). The analysis conducted in this study does not provide any insights as to what extent the campaign initiators are utilizing the existing support tools. An opportunity for further research and additional perspectives of the FMM is to study the use of methodologies and approaches for the crowdfunding teams. Such studies could include evaluations on the correlation between campaign success and use of design methodology, and could further evaluate whether crowdfunded product development introduces new challenges that call for dedicated 'design for crowdfunding' support tools.

#### 4.5.3. Use of prototypes in crowdfunding

Another research potential is related to design maturity and the prototypes presented in the campaign material. Recent advancement in rapid prototyping tools (Camburn *et al.* 2017) and collective design platforms (Özkil 2017) have made it possible to present high resolution 'looks like' prototypes in cheap and efficient ways. The results of our study document that campaigns with design for manufacture deficiencies are unlikely to deliver products in a timely manner. It is, however, widely unclear how mature the designs are, when they are presented on the crowdfunding platforms. Future studies, including further development and applications of FMM, could focus on prototypes and design maturity in their campaign material. This e.g. in combination with the 'Media Richness Theory' evaluations for optimal prototype fidelity, as introduced by Schmidt *et al.* (2017). Also, it could be investigated if a strong focus on 'looks like' prototypes introduces an inappropriate under prioritization on 'works like prototypes' with the ambition to advance design insights, such as the eliciting of unknown unknowns through prototype activities (Jensen, Elverum & Steinert 2017).

## 5. Conclusion

This paper provides an empirical review of the crowdfunding platform Kickstarter.com, with the aim of identifying challenges in crowdfunded product development, that consequently can cause in failure of the crowdfunding campaign. The analysis presented was built around a failure mode model, which was established through a pre-study. The first part of the analysis concerns the time aspect of the crowdfunding campaigns and presents an overview of the campaigns' ability meet their deadlines in delivering products to campaign backers. The



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

next part focuses on product evaluations made by the campaign backers and the campaign initiators' ability to deliver on promises concerning product features and attributes is quantified. Where the two first parts of the analysis concerns the promises made to campaign backers, the third part investigates challenges in the product development process by identifying and quantifying issues and challenges, which could cause the campaigns to fail in meeting their promises to backers.

The results of this study provide insights on crowdfunded product development through Kickstarter.com, and the authors expect that the results could be of relevance to both researchers and practitioners. Lastly, the study is also an example of how the crowdfunding platforms can be utilized in research as data libraries of product development cases.

## Acknowledgments

The authors would like to thank Design Science editors and reviewers, who provided insightful, constructive and timely comments and feedback!

## References

**Agrawal, A. K.**, **Catalini, C.** & **Goldfarb, A.** 2013 Some simple economics of crowdfunding. National Bureau of Economic Research.

**Amazon Launchpad** 2017 URL https://www.amazon.com/gp/launchpad/signup.

**Anderson, E. T.** & **Simester, D. I.** 2014 Reviews without a purchase: low ratings, loyal customers, and deception. *Journal of Marketing Research* **51**, 249–269.

**Aulet, B.** 2013 *Disciplined Entrepreneurship: 24 Steps to a Successful Startup*. John Wiley & Sons.

**Ball, Z.** & **Lewis, K.** 2018 Observing network characteristics in mass collaboration design projects. *Design Science* **4**, e4.

**Bannerman, S.** 2013 Crowdfunding culture. *Wi Journal of Mobile Media* **7** (1), 1–30.

**Bayus, B. L.**, **Jain, S.** & **Rao, A. G.** 2001 Truth or consequences: an analysis of vaporware and new product announcements. *Journal of Marketing Research* **38**, 3–13.

**Belleflamme, P.**, **Lambert, T.** & **Schwienbacher, A.** 2014 Crowdfunding: tapping the right crowd. *Journal of Business Venturing* **29**, 585–609.

**Berthon, P. R.**, **Pitt, L. F.**, **McCarthy, I.** & **Kates, S. M.** 2007 When customers get clever: managerial approaches to dealing with creative consumers. *Business Horizons* **50**, 39–47.

**Blank, S.** 2012 *The Startup Owner's Manual: The Step-by-Step Guide for Building a Great Company*. BookBaby.

**Blessing, L. T. M.**, **Chakrabarti, A.** & **Wallace, K. M.** 1998 An overview of descriptive studies in relation to a general design research methodology. In *Designers*, pp. 42–56. Springer.

**Boisseau, É.**, **Omhover, J.-F.** & **Bouchard, C.** 2018 Open-design: a state of the art review. *Design Science* **4**, e3.

**Bolt** 2017 Bolt. URL https://blog.bolt.io/ (accessed 4.15.18).

**Brabham, D. C.** 2008 Crowdsourcing as a model for problem solving: an introduction and cases. *Convergence: The International Journal of Research into New Media Technologies* **14**, 75–90; doi:10.1177/1354856507084420.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

**Brenner, W.**, **Karagiannis, D.**, **Kolbe, L.**, **Krüger, D.-K. J.**, **Leifer, L.**, **Lamberti, H.-J.**, **Leimeister, J. M.**, **Österle, H.**, **Petrie, C.** & **Plattner, H.** et al. 2014 User, use & utility research. *Business Information Systems Engineering* **6**, 55–61.

**Camburn, B.**, **Viswanathan, V.**, **Linsey, J.**, **Anderson, D.**, **Jensen, D.**, **Crawford, R.**, **Otto, K.** & **Wood, K.** 2017 Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science* **3** (13), 1–33.

**Chesbrough, H. W.** 2003 *Open Innovation: The New Imperative for Creating and Profiting from Technology*. Havard Bus. Press, doi:10.5465/AMP.2006.20591014.

**Colombo, M. G.**, **Franzoni, C.** & **Rossi-Lamastra, C.** 2015 Internal social capital and the attraction of early contributions in crowdfunding. *Entrepreneurship Theory and Practice* **39**, 75–100.

**Cumming, D. J.**, **Leboeuf, G.** & **Schwienbacher, A.** 2015 *Crowdfunding Models: Keep-It-All versus All-Or-Nothing (SSRN Scholarly Paper No. ID 2447567)*. Social Science Research Network.

**Dragon Innovation** 2016 Top 10 Manufacturing Reasons Hardware Companies Fail. URL https://blog.dragoninnovation.com/2016/09/08/top-10-manufacturing-reasons-hardware-companies-fail/.

**Einstein, B.** 2015a The illustrated guide to product development (part 1: ideation). Bolt Blog. URL https://blog.bolt.io/the-illustrated-guide-to-product-development-part-1-ideation-ab797df1dac7#.harn8xqx4.

**Einstein, B.** 2015b The illustrated guide to product development (part 3: engineering). Bolt Blog. URL https://blog.bolt.io/the-illustrated-guide-to-product-development-part-3-engineering-440b94de997a.

**Einstein, B.** 2015c Kickstarter! = Product/Market Fit. Bolt Blog. URL https://blog.bolt.io/kickstarter-product-market-fit-95f2b13ae75f#.dy6ji1231.

**Etter, V.**, **Grossglauser, M.** & **Thiran, P.** 2013 *Launch Hard or Go Home!: Predicting the Success of Kickstarter Campaigns*, pp. 177–182. ACM Press.

**Forbes, H.** & **Schaefer, D.** 2017 Social product development: the democratization of design, manufacture and innovation. *Procedia CIRP* **60**, 404–409.

**Gerber, E. M.** & **Hui, J.** 2013 Crowdfunding: motivations and deterrents for participation. *ACM Transactions on Computer-Human Interaction* **20** (6), 34.

**Gerber, E. M.**, **Hui, J. S.** & **Kuo, P.-Y.** 2012 Crowdfunding: why people are motivated to post and fund projects on crowdfunding platforms. In *Proceedings of the International Workshop on Design, Influence, and Social Technologies: Techniques, Impacts and Ethics*.

**Greenberg, M. D.**, **Pardo, B.**, **Hariharan, K.** & **Gerber, E.** 2013 Crowdfunding support tools: predicting success & failure. In *CHI'13 Extended Abstracts on Human Factors in Computing Systems*, pp. 1815–1820. ACM.

**Haas, P.**, **Blohm, I.** & **Leimeister, J. M.** 2014 An empirical taxonomy of crowdfunding intermediaries. In *35th International Conference on Information Systems "Building a Better World Through Information Systems", ICIS 2014*, Association for Information Systems.

**Harris, J.** 1985 *A Statue for America: The First 100 Years of the Statue of Liberty*. Four Winds Press.

**He, Y.** & **Luo, J.** 2017 The novelty 'sweet spot' of invention. *Design Science* **3**, e21.

**Hendricks, K. B.** & **Singhal, V. R.** 1997 Delays in new product introductions and the market value of the firm: the consequences of being late to the market. *Management Science* **43**, 422–436.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

**Herzenstein, M.**, **Sonenshein, S.** & **Dholakia, U. M.** 2011 Tell me a good story and I may lend you money: the role of narratives in peer-to-peer lending decisions. *Journal of Marketing Research* **48**, S138–S149.

**Jensen, M. B.**, **Elverum, C. W.** & **Steinert, M.** 2017 Eliciting unknown unknowns with prototypes: introducing prototrials and prototrial-driven cultures. *Design Science* **49**, 1–31.

**Kickstarter** 2016 OPLØFT. Kickstarter. URL https://www.kickstarter.com/projects/584258111/oplft-make-your-desk-height-adjustable.

**Kickstarter.com** 2016 www.kickstarter.com. URL https://www.kickstarter.com/help/stats?ref=foote.

**Koch, J.-A.** & **Siering, M.** 2015 Crowdfunding success factors: the characteristics of successfully funded projects on crowdfunding platforms.

**Kuo, T.-C.**, **Huang, S. H.** & **Zhang, H.-C.** 2001 Design for manufacture and design for 'X': concepts, applications, and perspectives. *Computers & Industrial Engineering* **41**, 241–260.

**Kuppuswamy, V.** & **Bayus, B. L.** 2015 A review of crowdfunding research and findings, *Handbook of New Product Development Research, Forthcoming*. Available at SSRN: https://ssrn.com/abstract=2685739, http://dx.doi.org/10.2139/ssrn.2685739.

**Marom, D.**, **Robb, A.** & **Sade, O.** 2016 *Gender Dynamics in Crowdfunding (Kickstarter): Evidence on Entrepreneurs, Investors, Deals and Taste-Based Discrimination (SSRN Scholarly Paper No. ID 2442954)*. Social Science Research Network.

**Massolution** 2015 2015CF Crowdfunding industry report. URL http://reports.crowdsourcing.org/?route=product/product&product_id=54 (accessed 11.21.16).

**Massolution, Crowdsourcing LLC** 2012 Crowdfunding industry report: market trends, composition and crowdfunding platforms. *Research Report*. Available at: www.crowdfunding.nl/wp-content/uploads/2012/05/92834651-Massolution-abridged-Crowd-Funding-Industry-Report1.pdf.

**Mollick, E.** 2015 Delivery Rates on Kickstarter. Retrieved from https://repository.upenn.edu/mgmt_papers/210.

**Mollick, E.** 2014 The dynamics of crowdfunding: an exploratory study. *Journal of Business Venturing* **29**, 1–16.

**Mollick, E. R.** & **Kuppuswamy, V.** 2014 After the campaign: outcomes of crowdfunding. UNC Kenan-Flagler Res. Pap.

**Moritz, A.** & **Block, J. H.** 2016 Crowdfunding: a literature review and research directions. In *Crowdfunding in Europe*, pp. 25–53. Springer.

**Ordanini, A.**, **Miceli, L.**, **Pizzetti, M.** & **Parasuraman, A.** 2011 Crowd-funding: transforming customers into investors through innovative service platforms. *Journal of Service Management* **22**, 443–470.

**Özkil, A. G.** 2017 Collective design in 3D printing: a large scale empirical study of designs, designers and evolution. *Design Science* **51**, 66–89.

**Partington, D.** 2000 Building grounded theories of management action. *British Journal of Management* **11**, 91–102.

**Pepitone, J.** 2012 Why 84% of Kickstarter's top projects shipped late. CNNMoney. URL http://money.cnn.com/2012/12/18/technology/innovation/kickstarter-ship-delay/index.html.

**Ries, E.** 2011 *The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses*. Random House LLC.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

**Schmidt, T. S.**, **Wallisch, A.**, **Böhmer, A. I.**, **Paetzold, K.** & **Lindemann, U.** 2018 Media richness theory in agile development choosing appropriate kinds of prototypes to obtain reliable feedback. *2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, Ice/itmc 2017, Proceedings 2018*, pp. 521–530.

**Schwienbacher, A.** & **Larralde, B.** 2010 *Crowdfunding of Small Entrepreneurial Ventures*. Handb. Entrep. Finance Oxf. Univ. Press, Forthcoming.

**Shimizu, H.**, **Imagawa, T.** & **Noguchi, H.** 2003 Reliability problem prevention method for automotive components-development of GD 3 activity and DRBFM (design review based on failure mode). *SAE Technical Paper*.

**Song, C.**, **Luo, J.**, **Hoelttae-Otto, K.**, **Seering, W.** & **Otto, K.** et al. 2015*a* Risk and innovation balance in crowdfunding new products. In *DS 80-8 Proceedings of the 20th International Conference on Engineering Design (ICED 15). Vol 8: Innovation and Creativity, Milan, Italy, 27–30.07.15*.

**Song, C.**, **Luo, J.**, **Hölttä-Otto, K.**, **Otto, K.** & **Seering, W.** 2015*b* The design of crowd-funded products. In *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. V007T06A040–V007T06A040. American Society of Mechanical Engineers.

**Stamatis, D. H.** 2003 *Failure Mode and Effect Analysis: FMEA from Theory to Execution*. ASQ Quality Press.

**Statista** 2018 Statista. URL https://www.statista.com/study/13089/crowdfunding-statista-dossier/.

**Tan, J. J. Y.**, **Otto, K. N.** & **Wood, K. L.** 2017 Relative impact of early versus late design decisions in systems development. *Design Science* **3**, e12.

**Ulrich, E.** 2007 *Product Design and Development*. McGraw-Hill Higher Education.

**Voss, C.**, **Tsikriktsis, N.** & **Frohlich, M.** 2002 Case research in operations management. *International Journal of Operations and Production Management* **22**, 195–219.

**Walsh, H. S.**, **Dong, A.** & **Tumer, I. Y.** 2018 The role of bridging nodes in behavioral network models of complex engineered systems. *Design Science* **4**, doi:10.1017/dsj.2017.31.

**Xu, A.**, **Yang, X.**, **Rao, H.**, **Fu, W.-T.**, **Huang, S.-W.** & **Bailey, B. P.** 2014 Show me the money!: an analysis of project updates during crowdfunding campaigns. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 591–600. ACM.

**Yancey, S.** 2016 Is latenesss failure? Kickstarter. URL https://www.kickstarter.com/blog/is-lateness-failure.

**Yulman, N.**, **Terra, J.**, **Dunham, Z.** & **Gallagher, D.** 2017 Why Hardware Studio? | Hardware Studio. URL https://hardware.studio/articles/why-hardware-studio.

**Zheng, H.**, **Li, D.**, **Wu, J.** & **Xu, Y.** 2014 The role of multidimensional social capital in crowdfunding: a comparative study in China and US. *Information and Management* **51**, 488–496.

**Zhou, M.**, **Du, Q.**, **Zhang, X.**, **Qiao, Z.**, **Wang, A. G.** & **Fan, W.** 2015 Money Talks: A Predictive Model on Crowdfunding Success Using Project Description. In *Proceedings of the 21st Americas Conference on Information Systems (AMCIS), Puerto Rico*.



Downloaded from https://www.cambridge.org/core. DTU Library - Tech Info Ctr of Denmark, on 23 Oct 2018 at 10:26:48, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms. https://doi.org/10.1017/dsj.2018.14

# *Crowdfunded product development: A study of hardware start-ups*

Jensen, Lasse Skovgaard; Özkil, Ali Gürcan
Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

# Abstract
The recent years have witnessed a new generation of hardware start-up's utilizing new paradigms for seed stage funding of product development projects. One of these paradigms is reward based crowdfunding which over few years have developed into a billion-dollar industry. Through the collective support of the crowd, crowdfunding is claimed to be changing what gets made and who has the opportunity to make it. Crowdfunding is still a relatively new phenomenon in the nexus of entrepreneurship and engineering design research, and this paper provides a study of 9 hardware start-ups who have finalized crowdfunding campaigns and delivered products to their backers. It is the aim of the study to understand characteristics of crowdfunded product development, the composition of start-up design teams, and the design methodologies that they know and adopt. The study reveals (i) Five characteristics of crowdfunded product development. (ii) That crowdfunding might be lowering the barrier of entry for entrepreneurs in the hardware domain, but also that the presence experienced team members influence the start-up's ability to timely deliver products (iii) The teams make little use of known design methodology but are very active in physical prototyping. Better understanding of crowdfunded product development can provide guidance for entrepreneurs and serve as probes for future research.

Keywords:
Crowdfunding, Design methodology, Engineering design, Product development, Hardware entrepreneurship

# *Introduction*
Recent years have witnessed an increasing number of consumer products that are verified and brought to life through reward-based crowdfunding; where campaign initiators collect small amounts of capital from a 'crowd', develop products or services using these funds, and provide them as 'rewards' to their backers (Massolution, 2015). As the web-based platforms for crowdfunding like Kickstarter ("Kickstarter," 2018) and IndieGoGo ("Indiegogo," 2018) became popular, the market size for crowdfunded products grew exponentially. According to Kickstarter, more than 60,000 reward based campaigns – such as the Pebble smart watch, the Occulus Rift headset (Figure 1) and the Ouya gaming console - were launched in the 'Design' and 'Technology' category of the crowdfunding platform since it was founded in 2009. Collectively these campaigns received more than $1.1 billion dollars in funding ("Kickstarter Stats," 2017).

Consequently, crowdfunding has become an emerging field of research. From a diverse number of fields, researchers have investigated different aspects of crowd participation and funding; such as the economics of crowdfunding, product and pricing decisions, prediction of campaign funding success and cultural elements of participation (Agrawal et al., 2013; Bannerman, 2013; Du et al., 2015; Greenberg et al., 2013; Hu et al., 2015; Koch and Siering, 2015), (Martínez-Climent et al., 2018).

Exceeding the work covered in the work introduced above, crowdfunding also impacts entrepreneurship activities and design processes. This by creating new means of interactions between the designers and the 'crowds' of potential co-creators and consumers (Song et al., 2015). According to design and technology curators at Kickstarter a number of these campaigns, and the products and teams they concern, would never have been greenlighted by managers and investors in the established industry (Yulman et al., 2017). In this sense crowdfunding is affecting the actors in entrepreneurship communities by "changing what gets made and who has the opportunity to make it" (Yulman et al., 2017)

Despite the interplay between the rise of crowdfunding, entrepreneurship and new product development, there has been limited research on the topic and how products that are funded by the crowds are designed, managed and who the entrepreneurial creators are (Mollick, 2014a) (Mollick, 2015). From the existing body of literature, we know that team compositions and the individual characteristics of the designers and developers can have a profound effect on the product development processes (Pyatt, 1966). Further various studies from different industries have documented how the use of design methodologies can improve development processes and design outcomes (Chakrabarti and Lindemann, 2015). We however consider it uncovered how these topics unfolds in crowdfunded product development, and what particular characteristics might be affecting this paradigm. Hereby, this paper aims to provide an understanding for the characteristics of crowdfunded product development, by setting out the following questions:

- RQ1: How are teams in crowdfunded product development composed?
- RQ2: Which design methodologies are known and used in the design process of crowdfunded products?
- RQ3: What particular characteristics of crowdfunded product development can be identified?

This paper aims to address these questions through a study of nine start-ups that used crowdfunding to develop and release consumer-oriented hardware products. The data collected for the study consists of campaign data that was extracted from the crowdfunding platforms as well as data that were recorded through semi-structured interviews with the campaign initiators.


Figure 1 Oculus Rift is a virtual reality device that was launched on Kickstarter.com. It raised $2,437,429 from 9522 backers, and the company was later acquired by Facebook for $2,000,000,000 (Picture from Kickstarter Campaign at Kickstarter.com in 2012)

The rest of the paper is organized as follows. In section 2, we present the current state of research on design methodologies, start-ups and crowdfunding. The third section describes our methodology and describes how the data is collected and handled. Next, we provide an analysis of the data and discuss our findings. Finally, we conclude the paper with our reflections and provide directions for future research.

# *Background*

Reward-based crowdfunding refers to the action where campaign initiators collect small amounts of capital from a 'crowd' or relatively large number of people (Massolution, 2015). As the web-based platforms for reward-based crowdfunding like Kickstarter ("Kickstarter," 2018) and IndieGoGo ("Indiegogo," 2018) became popular, the market size for crowdfunded products grew exponentially. Since its launch in 2009 more than 10.000 hardware projects have been successfully crowdfunded, and the campaign backers have in all together pledged more than 3B$ on Kickstarter campaigns ("Kickstarter.com," 2016). Crowdfunding is especially attractive for small entrepreneurial start-ups, as the lack of early-stage funding historically has been a limit to their ability to develop products (Kuppuswamy and Bayus, 2015). A survey of 935 early-stage technology-based start-ups finds that 13,1% of the start-ups pursued a crowdfunding campaign, as funding source for their project (Rijnsoever et al., 2017).

## ***Crowdfunding research***

While crowdfunding campaigns can have different aims and ambitions, a typical crowdfunding campaign involves an open call through an internet-based campaign to secure financial resources, in the form of donations or in exchange for rewards, to support initiatives for specific purposes (Belleflamme et al., 2014). Rewards may vary significantly, based on the nature of the campaigns or the amount of financial support provided. Rewards can be tokens of appreciation ('thank you' messages, postcards, stickers, t-shirts) or pre-purchasing of products or services (Hemer, 2011). The focus of the study presented in this paper is on campaigns that aim to develop physical products, where campaign backers are offered the product(s) that are being developed as rewards.
There are only a few studies that have investigated crowdfunding campaigns from a longitudinal and product development perspective. For instance, Panchal outlines an analytical framework for designing crowdsourcing initiatives for design with a focus on framing problems, choosing the right type of crowdsourcing mechanisms, and

designing incentives (Panchal, 2015). In (Greenberg et al., 2015), the authors present a tool for gathering design critiques on crowdfunding campaigns from paid crowd-workers.

Forbes and Schaefer describe Social Product Development as an overarching term that extends open innovation beyond customer-involvement models to socially engaged individual actors fully involved in ideation and development of new products. This characterized as a 'playing field' for both engineering professionals and the members of the makers' communities; and claim that crowdfunding is an important part of Social Product Development (Forbes and Schaefer, 2017). Apart from being a possible source of funding for product development, crowdfunding is also important for the feedback, ideas and the word-of-mouth dissemination that crowds can provide (Stanko and Henard, 2016). While crowdfunding backers can be viewed as a preliminary category of early innovation adopters, the authors also report that not all campaigns are able to capitalize on their backers' passion and willingness to participate in product development (Stanko and Henard, 2017). As raising capital is usually a logical focus for many entrepreneurs, crowdfunding teams often underestimate the time, effort and costs associated with the development, manufacturing and fulfilment of the products (Hui et al., 2012).

The data that became available through the crowdfunding platforms also led to empirical studies in the design aspects of the crowdfunded products. In Song et al (Song et al., 2015), the authors collected various types of data for 3D printer and smart watch projects from the popular platforms Kickstarter and Indiegogo. The Real-Win-Worth (RWW) measure was used as an assessment framework (Day, 2007) to compare the projects that reached their funding goals to the ones that did not. Furthermore, the authors define 'success' as reaching the funding goals and use the results of the RWW analysis to identify key design characteristics for crowdfunding success. Similarly, Xu et al. analyzes the effect of crowd interaction during the fundraising phase and they further provide a taxonomy of campaign updates and investigate their effects on funding success (Xu et al., 2014).

While securing funding is a major milestone for crowdfunded product development, whether the designed product becomes a 'success' requires further investigation and understanding of the post-funding product development activities. For instance, Mollick reports that only 24.9% of campaigns deliver rewards on time, the majority of the campaigns are significantly delayed, and a proportion of them do not manage to deliver rewards at all (Mollick, 2014a).

## *Design Methods and Their Adoption*

Design approaches and methodologies aim to support designers by providing support and guidelines to improve the chances of producing successful products (Blessing et al., 1998). There is a large body of research on the use and usefulness of different design methodologies, methods and tools, and it is claimed that applying design methodology in product development processes can lead to superior financial performances, greater degree of innovativeness, better product quality, better cross-functional collaborations, higher team performances and shorter time-to-market (Graner, 2016) (Booker, 2012) (Herrmann et al., 2004), (Yeh et al., 2010), (Graner, 2016), (Chakrabarti and Lindemann, 2015).

The industrial adaption of research-based design methodologies and their effects on industrial practice are however also a debated topics (Suh, 1998) (Eder, 1998) (Chakrabarti and Lindemann, 2015)(Schmitt et al., 2015). For instance, it is argued that "most results end up in scientific publications rather than being transferred into practice" and both researchers and industry are claimed to be responsible for this failure to adopt design methods (Birkhofer, 2001), (Araujo et al., 2001). Araujo further argues that 'the tool makers' creating design methods have historically failed to market their work in an appealing format and also proposed methods which are too complicated or not fitting into 'real world' scope; whereas industry suffers from change inertia and have failed in understanding the methodologies and their potential benefits (Araujo et al., 2001). More recently, a study by Rajaeian et al. identified how an impact-minded approach from researchers was significantly more effective than publication-minded researchers in transferring knowledge to industry (Rajaeian et al., 2018)

In the start-up community two design support methodologies in particular have gained attention in recent years: "The Customer Development Model" (Blank, 2012) with its main theme on product success through a better understanding of customers and how to build a commercially successful company, and "The Lean Start-up" methodology (Ries, 2011), which has a strong focus on fast iterations and feedback loops utilizing the lead users (Frederiksen and Brem, 2017). According to the authors, these methodologies have been especially developed out of and for agile development in software start-ups but are now also being adapted by hardware start-ups (Blank, 2013). Furthermore, two business-oriented support methodologies are reported to be used by start-ups – the "Business Model Canvas" (Osterwalder and Pigneur, 2010) and the "St. Gallen Business Model" (Gassmann et al., 2013). These methodologies have business models as a central and integrated focus of the development process (Stock and Seliger, 2016). While it is probably not only one particular characteristic that have driven this increased attention, authors have pointed towards to argument that they tend to put focus on a few key ideas and that a simple recipe promising success and fortune is more interesting than the rigor of scientific literature (Frederiksen and Brem, 2017).

## *Design Teams*

The human capital – the prior knowledge, experience and capabilities that team members bring – is one of the most important assets of a company (Pyatt, 1966), (Kichuk and Wiesner, 1997). In the early stages of product development, novice designers have the advantage of having less bias, which can lead to more creative or innovative concepts, whereas the positive impact of knowledge and experience is more valuable in the later stages of product development, manufacturing and fulfilment.

In this regard, there are different views on what experience brings to the design processes and how it affects the success of start-ups. On one hand, educated and experienced employees in start-ups and technology companies have been shown to be more productive and to have a greater ability to solve problems extemporaneously and to fluidly adapt to changes (Wright et al., 2007). Similarly, the difference between experienced and novice founders is also found to be significant and it is reported that the experience is correlated with taking the right decisions and actions (Deininger et al., 2017), (Weber and Jung, 2015).

On the other hand, it is reported that knowledge and experience can also bring negative effects to product development, as prior knowledge and experience leads to a certain blindness regarding new opportunities and strong domain knowledge can inhibit innovation (Brockman, 2003) (Argyris, 1997). While innovative change and creativity in new product development can become more difficult with the increasing amount of information and data, it is also suggested that interdisciplinary teams possess more creativity, and capacity for innovation (Moorman and Miner, 1997).

While above mentioned studies contribute to the understanding of different aspects of reward based crowdfunding, the work presented in this paper differs from the previous work in three major aspects. First this paper aims to provide an understanding of the characteristics of crowdfunded product development after the campaign have been successfully funded. Second, we present our findings on how the design teams are composed. And finally, we report on which design methodologies are known and used in the development process. By recalling the statement that crowdfunding is "changing what gets made and who has the opportunity to make it" (Yulman et al., 2017) we find these topics being of particular relevance to the domains of entrepreneurship and new product development.

# Methods

Our analysis is based on campaign data that is extracted from crowdfunding platforms and data that is collected through semi structured interviews with start-ups that have launched, and successfully funded, crowdfunded product development campaigns.

## *Participants*

Crowdfunding platforms as Kickstarter and IndieGoGo can be considered as rich data libraries of entrepreneurial product development cases. The following list illustrates our selection criteria for the campaigns included in this study:

- Campaign period: To be able to understand the challenges that are faced after successful funding, we have focused on the campaigns that ran in the period of 2013-2016. This ensures that the teams had at least one year to deliver the products to their backers.

- Platforms: Kickstarter.com and Indiegogo.com are the two leading platforms, and we have selected campaigns that ran on either of these platforms.

- Complexity: Campaigns that were targeted for makers or prosumers (e.g. 3D printers) and campaigns that had limited complexity (e.g. kitchen towels) were not considered.

- Availability of the interviewees: To be able to understand the whole product development journey, we have identified the ideal interviewees as the founders or co-cofounders who initiated the campaigns and had major responsibilities in engineering and product development activities. Furthermore, the interviewees were expected to possess a general overview of all operational activities within the company.

Based on these criteria, we approached 13 start-up companies, 9 of which volunteered to participate in the interviews. Table 1 provides an overview of the start-ups we have investigated. Upon request of the participants, details of the interviews are restricted to product development related activities, preserving the participants' anonymity and details of their operations and business partners.

Table 1 Overview of companies selected for the study including information on interviewee title, amount of capital funded through crowdfunding campaign and the number of backers

| | **Company / Case** | **Interviewee(s) Titles / Responsibilities** | **Campaign funding result (€)** | **No. of Backers** |
|---|---|---|---|---|
| 1. | Mechanical furniture product for improved ergonomics | 1. Lead Mechanical Engineer<br>2. Crowdfunding campaign responsible | 59 234,- | 212 |
| 2. | Consumer Hi-Fi system | 1. Chief Technology Officer<br>2. Chief Financial Officer | 39 187,- | 112 |
| 3. | Portable product with seating functionality | 1. Lead Mechanical Engineer | 135 734,- | 2.749 |
| 4. | External smartphone sensor for wind measurement | 1. Chief Technology Officer | 35 201,- | 917 |
| 5. | Motion tracking system for video and gaming | 1. Vice President of Product | 106 836,- | 223 |
| 6. | Video streaming device | 1. Chief Product Officer | 1 385 915,- | 14 162 |
| 7. | Smart home security device | 1. Chief Executive Officer | 214 840,- | 2 005 |
| 8. | Consumer Hi-fi system for outdoor use | 1. Head of Development | 706 910,- | 1 559 |
| 9. | Digital music instrument | 1. Lead Designer | 561 401,- | 4 064 |
| | | **Total**: | **3 245 258 €** | **26 003** |

## *Interview protocol*

To be able to collect data that is comparable across the interviews, we have used a semi-structured interview approach and used a checklist of topics to steer the discussion. This checklist is developed into an interview guide, which consists of five main themes:

1. **General information on the company:** Number of employees, team composition, operation time, vision and nature of funding in the organization.
2. **Interviewee and team backgrounds**: Educational and practical experiences, current focus and responsibilities.
3. **Crowdfunding campaign and outcome**: Objective of choosing crowdfunding, delays in delivery, engagement with backers.
4. **Product development and crowdfunding:** Development phases and timeline, specific challenges related to crowdfunding.
5. **Design methodologies in product development:** Methodologies, methods and tools used for design and management processes.

Besides the thematic structure, the interview protocol also included different tools to be used during the interviews. These include the timeline format to describe campaign delays (Mollick, 2014a), multiple choice questions on motivation for using Crowdfunding (Mollick, 2015), self-evaluation of the design maturity at campaign launch.

One of the central aspects of our study was to investigate what support and design methodologies are used in crowdfunded product development. To systematize the collection of data we have adopted the list of methodologies compiled by (Stock and Seliger, 2016), and surveyed the interviewees to document their design team's prior knowledge and use of the methodologies. These include:

1. *Methodologies based on product development phases* such as: VDI 2221 (*VDI 2221*, 1993), "Engineering Design: A systematic approach" (Pahl and Beitz, 2013), Concept Development & Design of technical products" (Ponn and Lindemann, 2011), "Methodological Development of technical products" (Lindemann, 2005) and "The process of product creation" (Albers and Braun, 2011). Methodologies in this category are characterized by a phase-focused approach to product development and generally have prescribed objectives related to each phase.
2. *Methodologies based on systems engineering* as e.g. described by the VDI 2206 (*VDI 2206*, 2004), "Model based virtual product development" (Eigner et al., 2014) and "The W-model: Systems Engineering in the development of active systems" (Nattermann and Anderl, 2013). These methodologies apply a top-down approach where simulation and virtual modelling allows for a system approach.
3. *Methodologies based on design principles* such as "Design for X" (Eastman, 2012) and "Lean Development" (Hoppmann et al., 2011). Design principles and their application in product development are the characteristic for these methodologies.
4. *Methodologies based on integrated approaches* as developed e.g. by "Integrated Product Development" (Ehrlenspiel and Meerkamm, 2013) and "Integrated Design Engineering" (Vajna et al., 2009). These methodologies are holistic and strive to include social, organizational and technological perspectives.

In addition to the list above, we also included other methodologies expected to be of relevance, such as;

1. Traditional approaches: "Stage Gate Model" (Cooper, 1990) and the "Waterfall Model" (Royce, 1987);
2. Popular methodologies that stem from innovation management: "The Customer Development Model" (Blank, 2012), "The Lean Start-up" methodology (Ries, 2011) and "Business Model Canvas" (Osterwalder and Pigneur, 2010). "Design Thinking" (Brown, 2009) was also added to the list as it shares many similarities with The Lean Start-up approach (Müller and Thoring, 2012).
3. Agile methodologies: "Agile Development" ("Manifesto for Agile Software Development," 2001) and "SCRUM" (Takeuchi and Nonaka, 1986), as they are reported to be popular among software start-ups (Paternoster, 2014) but have emerged into development of physical hardware products (Böhmer et al., 2017b), (Böhmer et al., 2017a).

Finally, to ensure an inductive approach, interviewees were also asked to mention the methodologies they used, that were not included in the list. The full list of methodologies can be seen in Table 2.

## *Data collection and analysis*

Prior to the interviews the crowdfunding campaign material for each campaign was studied in order to establish a holistic background and understanding of the participant's projects. This part of the study is based on three data sources:

1. **The campaign description page;** which typically contain a short 'marketing' video, followed by an in depth article that provides information on various aspects of the project**.**
2. **Frequent updates by project initiators***;* concerning the progress of their campaigns. Updates are posted in a blog like format and can vary from quick status updates to e.g. detailed statements on manufacturing challenges.
3. **Comments by backers;** which provide continuous feedback and constructive critic during the projects.

Interviews were conducted at the companies' premises. Due to the semi-structured nature of the interviews, the interview data also includes anecdotes and discussions on particular issues highlighted in the crowdfunding campaign material. The overall interview structure was however kept in a similar format at all interviews. The interviews lasted from 75 minutes to 102 minutes with an average length of 89 minutes.

The interview protocol was developed using the principles described in (Eisenhardt, 1989) and it includes project timelines, multiple choice questions, perceived maturity evaluations and the survey of product development methodologies. These tools were included in the interview protocol to support the dialogue but also allowed us to directly code a number of interview questions. During and directly preceding the interviews, the findings for each start-up were summarized in detailed notes, which also included descriptive data previously collected from the crowdfunding platforms. The interviewees reviewed and cross-checked these notes to ensure accuracy and reliability. Finally, the full interviews were also audio recorded and subsequently coded to establish themes and other relations across the point of view and described practices for each start-up. The results of the coding process are reflected in the five characteristics of crowdfunded product development which are presented in the results.

# *Results*

The following sections outline our findings over the three main themes, focusing first on the design teams and their composition then followed by evaluations of their knowledge and use of design methodologies. Finally, we present characteristics of 'crowdfunded product development', which have emerged from patterns in the conducted interviews

## *Educational and Professional Experience of the Team Members*

Team compositions and the individual characteristics of the designers and developers can have a profound effect on the product development processes. Based on the literature presented in the previous section, our analysis focuses on three aspects of the development teams: (i) Formal education with engineering design focus. (ii) Previous experience from a hardware start-up with new product launch. (iii) +5 years professional working experience in product design and development at established company.

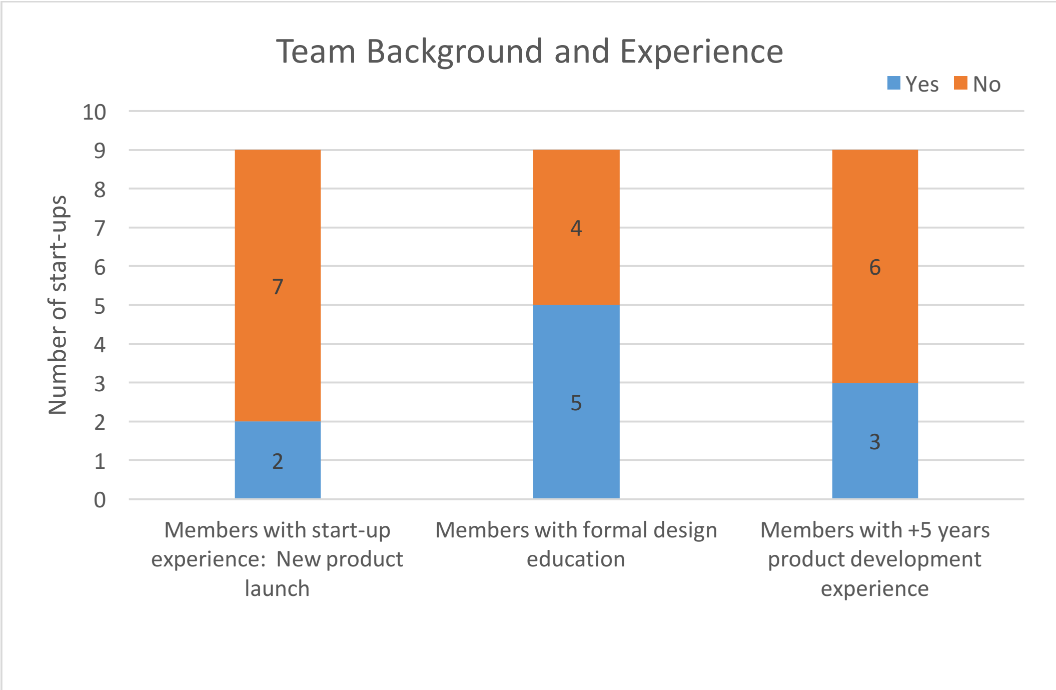



Figure 2 *Distribution of the team members' experience in the three themes: (i) Formal education with engineering design focus. (ii) Previous experience from a hardware start-up with new product launch. (iii) +5 years professional working experience in product design and development at established company*

Figure 2 summarizes the levels of experience the start-up teams possess. Crowdfunded product development is rather new to the majority of the start-ups, and only two of the teams had members with previous experience in bringing a product to market and shipping to customers. Similarly, the majority of the teams did not have any members that could bring their previous professional experience to the crowdfunded product development tasks. Five of the teams had members with formal education in (engineering/industrial) design and product development. While it is considered to be an advantage, the following sections further investigate how and to what extent the knowledge acquired in an educational program is used in crowdfunded product development.

Different types of experiences are not mutually exclusive, and teams can have members who have formal design education, significant professional experience and experience in shipping products, at the same time. On the other hand, it is also possible to launch campaigns and develop products without possessing any of the above, due to the nature and the dynamics of crowdfunding. Despite the limited sample size of this study the results provide evidence that crowdfunding might be lowering the entry barrier for teams of hardware entrepreneurs with limited start-up experience.

At the time of launching the crowdfunding campaign the teams were on average 3,8 fulltime employees and they had on average 13,1 employees at the time of the interviews.

## *Team Backgrounds*

Figure 3 summarizes the backgrounds of the founding members of the start-ups. The majority of the 34 founders have technical backgrounds, either in terms of formal engineering degrees (17) or they became technical experts by trade (2). Furthermore, despite their relatively small sizes the majority of the start-ups were formed by teams with cross-disciplinary backgrounds. Finally, start-up 8 represents an interesting case, where one team member has a +5 years' experience as an electrical engineer, and the remaining team members just finished high school and due to their young age, have no prior product development education or experience.

Looking at the founders with technical backgrounds, we see that seven candidates have formal educations in mechanical and/or design engineering, six in computer science, four in electrical engineering and two in materials science engineering. In this regard, it is expected that the backgrounds of the founding team members would influence the work practices of the start-up teams in selection and adoption of design methodologies in product development. The following section provides further findings on the adoption of design methods in crowdfunded product development.

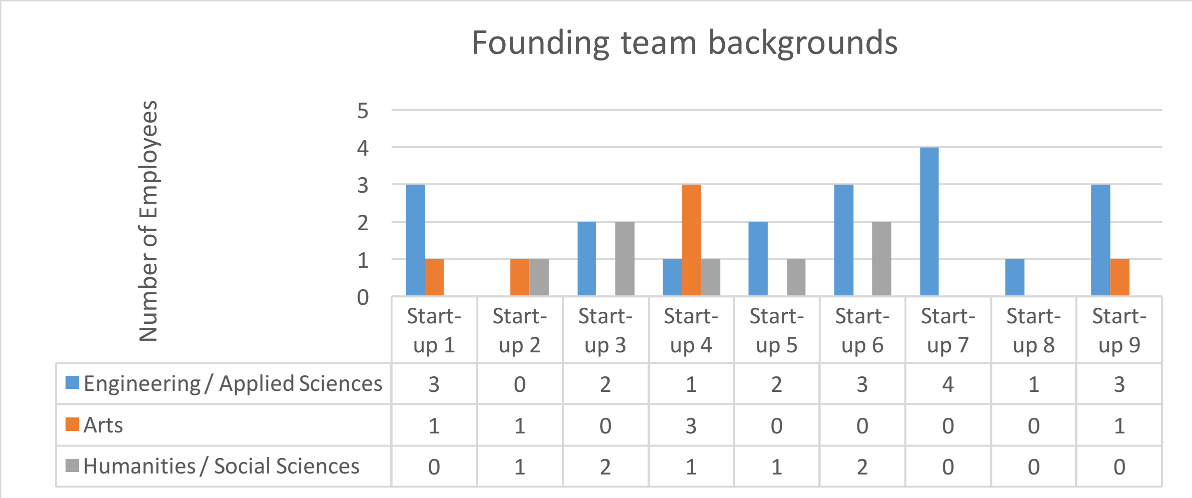



*Figure 3 Overview of the educational backgrounds of the founding start-up team members at time of campaigning. Founders with backgrounds in engineering and applied sciences account for the majority. Two employees from start-up No. 8 are not listed due to their young age (with recent high school qualifications)*

## *Adoption of Design Methods*

As discussed previously, the impact of design research on the industry has been a topic of debate. While there are different viewpoints and opposing reports on the adoption of the design methodologies from different industries (Chakrabarti and Lindemann, 2015), (Andreasen, 2011), (Araujo et al., 2001), there is only very limited information on what tools and methods are used by start-ups and crowdfunded product development teams.

We set out to understand what methodologies crowdfunded product development teams are familiar with and which ones they utilized in their product development processes. The interview protocol included a composed list of design methodologies, which were presented to the interviewees to facilitate a structured discussion on the adoption of the methods. Tables 2 summarize the responses, and respectively present the interviewees prior knowledge of design methodologies and their experience in using them during the development of their (crowdfunded) products.

Table 2 shows a few visible patterns; six of the twenty methodologies presented were unknown to the interviewees and four of them were only heard of but not used. The interviewees had varying experiences with the remaining ten methodologies. Methodologies that originate from business or software domains – Lean Start-up, Business Model Canvas, Agile development and Scrum - are the most widely known methods, whereas the remaining methodologies has intermediate levels of domestication among the start-ups.  Five methodologies that were unknown can be mainly characterized by their focus on product development through specific phases or systems engineering. Also the St. Gallen Business Model, despite its focus on start-ups, was unknown to the interviewees.

*Table 2 Overview of interviewees' prior knowledge of product development methodologies ("known" rows) and methodologies specifically used for the crowdfunding project ("Used" rows). The numbers represent respectively: 1: "Have previous experience with this methodology", 2: "Have previously heard about this methodology", 3: "Never heard of this methodology before", 4: "Used before & in crowdfunding project", 5): "Used before but not used for crowdfunding project", 6: "Heard about before & not used for crowdfunding project". Gray color: "Unknown to the interviewee and never used". Asterisk: "Used in crowdfunding but not before"*

| **Knowledge of Design Methodologies & Design Methodologies Used** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | **Start-ups** | | | | | | | | |
| **Model** | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Stage Gate model (Cooper, 1990) | Known: | 1 | 3 | 2 | 3 | 2 | 3 | 3 | 3 | 3 |
| | Used: | 5 | 0 | 6 | 0 | 6 | 0 | 0 | 0 | 0 |
| Waterfall Model (Royce, 1987) | Known: | 2 | 2 | 2 | 3 | 2 | 1 | 2 | 3 | 2 |
| | Used: | 6 | 6 | 6 | 0 | 6 | 5 | 6 | 0 | 6 |
| Agile Development | Known: | 2 | 3 | 1 | 1 | 1 | 1 | 2 | 3 | 1 |
| | Used: | 6 | 0 | 5 | 5 | 5 | 4 | 4 | 0 | 4 |
| SCRUM (Takeuchi and Nonaka, 1986).) | Known: | 2 | 3 | 1 | 1 | 1 | 1 | 2 | 3 | 1 |
| | Used: | 5 | 6 | 5 | 5 | 4 | 4 | 6 | 0 | 4 |
| Design Thinking (Brown, 2009) | Known: | 2 | 3 | 2 | 2 | 2 | 2 | 1 | 3 | 1 |
| | Used: | 4* | 0 | 6 | 6 | 6 | 6 | 4 | 0 | 6 |
| The Customer Development Model (Blank, 2012) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 1 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 |
| The Lean Start-up (Ries, 2011) | Known: | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| | Used: | 4 | 4 | 6 | 6 | 4 | 4 | 4 | 4 | 4 |
| VDI2206 (*VDI 2206*, 2004) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VDI 2221 (*VDI 2221*, 1993) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Engineering Design: A Systematic Approach (Pahl and Beitz, 2013) | Known: | 2 | 3 | 2 | 3 | 3 | 2 | 3 | 3 | 3 |
| | Used: | 6 | 0 | 6 | 0 | 0 | 6 | 0 | 0 | 0 |
| Concept development & design of technical products (Ponn and Lindemann, 2011) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Methodical development of technical products (Lindemann, 2005) | Known: | 2 | 3 | 2 | 3 | 2 | 3 | 3 | 3 | 3 |
| | Used: | 6 | 0 | 6 | 0 | 6 | 0 | 0 | 0 | 0 |
| The process of product creation (Albers and Braun, 2011) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| The W-Model: Engineering in the Development of active systems (Nattermann and Anderl, 2013) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Model based virtual product development (Eigner et al., 2014) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| "Design for X" (Eastman, 2012) | Known: | 1 | 3 | 1 | 2 | 2 | 2 | 3 | 3 | 3 |
| | Used: | 4 | 0 | 4 | 6 | 6 | 6 | 0 | 0 | 0 |
| "Lean Development" (Hoppmann et al., 2011) | Known: | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 3 | 2 |
| | Used: | 0 | 0 | 6 | 6 | 6 | 6 | 6 | 0 | 6 |
| Integrated Product Development (Ehrlenspiel and Meerkamm, 2013) | Known: | 3 | 3 | 2 | 3 | 2 | 3 | 3 | 2 | 3 |
| | Used: | 0 | 0 | 6 | 0 | 6 | 0 | 0 | 6 | 0 |
| Integrated Design Engineering (Vajna et al., 2009) | Known: | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 6 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 |
| The Business Model Canvas (Osterwalder and Pigneur, 2010) | Known: | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 |
| | Used: | 6 | 4 | 4 | 4 | 4 | 4 | 4 | 6 | 6 |
| St. Gallen Business Model" (Gassmann et al., 2013) | Known: | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Used: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

The adoption of the methods naturally depends on the previous knowledge of the existing methods; Table 2 summarizes the methods used by the start-ups in their crowdfunding campaigns. The business model canvas and Lean start-up models are the only methods that have a broad adoption among the interviewees. While ‘Design for X’ was adopted by two start-ups (1) & (3) that develop mechanical products. Agile Development and SCRUM was used by the start-ups that develop software intensive products. A conscious choice not to utilize these methodologies (despite previous experiences) was made by start-ups (1) & (3). Also, start-up (4) made this decision despite software being an essential aspect of their mechatronic products. A pattern in the decision not to adapt Agile Development and SCRUM was the argument that they are not suitable for development of physical hardware products.
The adoption of Design Thinking was mentioned by two start-ups; while one of the start-up (7) presented previous experience as their main motivation, the other start-up (1) referred to their educational background in engineering design. Further, the use of ‘Design Thinking’ by start-up (1) was the only example of a methodology adapted without prior experience in using it.
Apart from the list of methodologies presented to the start-ups, the interviewees were also asked if any other methodology was used. A pattern emerged around this question as five out of nine start-ups reported use of the online and Kanban based platform named Trello.com to organize and distribute tasks. Furthermore, three start-ups reported to periodically use Gantt Charts or different adaptions of the main principles of such charts. The start-ups (2) & (5) described that their design processes are driven by a stepwise ‘learn as we go’ design progress through prototyping and that they considered this a substitute for written documentation. In the discussion we elaborate on the use of respectively Trello.com, Gantt Charts and prototyping in the design process.

## *Characteristics of Crowdfunded Product Development*

Crowdfunded product development is a rather new phenomenon and its characteristics are not well known. Based on the interview guide the discussions with the interviewees and subsequent coding hereof, we have identified five main areas where crowdfunding acts as an important constituent in entrepreneurship and product development. These are: (i) Design maturity levels at the time of funding (ii) Leveraging external investment (iii) Managing deadlines (iv) Crowd feedback and co-creation and (v) Professional Business Backers. We consider these insights equally relevant for practitioners as well as researchers with an interest in the topic.

### *Perceived Design maturity levels*

In order to launch a product oriented funding campaign on Kickstarter and Indiegogo, the teams are required to show ‘works like’ and ‘looks like’ prototypes in their campaign material and convince the crowds that they are at almost manufacturing-ready state. While the initial phases of a crowdfunding campaign revolve around achieving a proof of concept prototype that can be marketed to masses, the post funding phase is mostly about designing an actual product that is reliable and can be manufactured. This often creates a strong shift of focus for the funded campaigns and naturally brings the maturity of designs into question.

To better understand this issue, we have asked the interviewees to evaluate the perceived maturity levels of their products at the time of campaign launch and the percentage of overall time spent for product development until campaign funding. The variation in perceived maturity varies significantly among the start-ups; while some of them had mature designs tested through several prototyping cycles, the others only had early proof-of-concept prototypes that were far from manufacturing-ready prototypes (Figure 4). The overall maturity of the products at the time of the crowdfunding campaign was 36%. Furthermore, all start-ups expressed and described that ‘wizard of oz’ prototyping - staging some of their products’ functionality – was necessary to produce the campaign material and the prototypes shown in the campaign videos were not %100 functional.

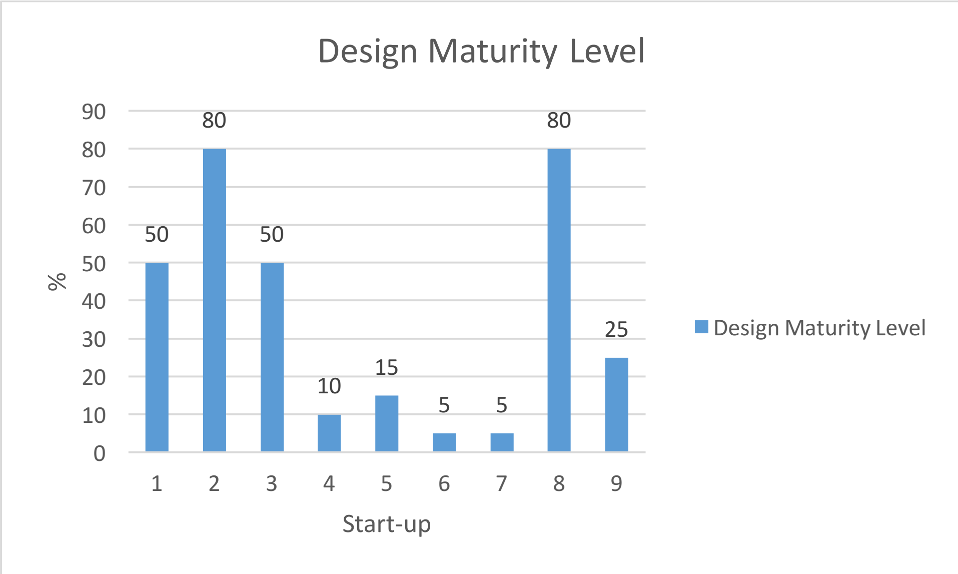



*Figure 4 Percentagewise maturity level of the product design at the time of campaign start where 0% is starting point of design process and 100% is a fully design layout ready for manufacturing*

Some uncertainty is to be expected in the comparability of how the interviewees perceived their maturity. However, the wide variation in maturity levels indicate that the teams chose different strategic approaches to their crowdfunding and product development process. Validation of the market potential and obtaining marketing traction were through articulated as a shared common motivation for all start-ups on the question why they initially chose to launch a crowdfunding campaign. In this light, the teams with low maturity levels at campaign start, utilized the opportunity to achieve early proof-of-market. This as a tempting trade-off on “selling skins before they were hatched” with potential inertia introduced by the campaign commitments and potential design challenges calling for product redesigns later in the design process.

### *Leveraging external investment*

Development of physical products and associated manufacturing and fulfilment processes often require substantial financial resources. Raising the funds to cover these costs is an essential activity for many start-ups. We find a relation between reaching crowdfunding goals and start-ups’ ability to attract external venture capital; All but one of the start-ups received external funding after their campaign was concluded. All interviewees agreed on the statement that successful crowdfunding campaigns was the most important leverage for later negotiations with potential investors in securing acceptable evaluations of the company value. Four start-ups (2, 3, 6, 8) further claimed that they would not be able to raise external funding for their project without the result of the crowdfunding campaign as documentation for market interest. Whereas it might seem obvious that validation and documentation are important parameters in valuation and term negotiations with potential investors, we highlight that market validations through crowdfunding might be developing into a ‘need to have’ validation for hardware start-ups in search for the additional capital needed to launch products in consumer markets.

### *Co-creation and community influence on design*

In crowdfunding, backers can engage in dialogue with campaign initiators and provide design inputs and insights. Such behaviour is a known phenomenon in online and crowdsourcing communities (Chang and Lee, 2018) and shares some similarities with the notion of Lead Users by Von Hippel (Von Hippel, 1986) and the Creative Consumers phenomenon by (Berthon et al., 2007). Furthermore, the participatory nature of crowdfunded product development is a motivation for some of the backers to support these campaigns and they expect a continuous dialogue and an inclusive process from the campaign initiators.

All of the eleven interviewees underlined that the continuous dialogue with the community, especially during the campaign phase, was a central part of their campaign and they acknowledged that the possibility to obtain design inputs from the community could benefit their development activities. On the other hand, the crowds’ influence on the final delivered products– besides their economic contribution – were minimal for the participants in this study. Only Start-up

(9) reported that they actively used their backers' feedback as design inputs. One example of this behavior is indicated in Figure 5 below, where a design input from a backer is noted and passed to the development team.


*Figure 5 Clipping of dialogue between campaign creator and a backer during the campaign funding period. The backer provides feedback on the working principle of the product, which is taken notice of by the creator*

The nine start-ups we interviewed had 2880 backers on average and an active dialogue that is desired by the community can be a very resource demanding task for such small teams. The majority of the start-ups reported that interaction with the crowd is very time consuming, and it is generally seen as a burden because backers' feedback was often unstructured and outside the scope of the development process.

### *Slipping deadlines – a public pillory*

Setting deadlines for the delivery of the products is an essential part of a crowdfunded product development process. Given the uncertainties faced by development teams and their desire to attract as much funding as possible from individuals, deadlines advertised during the funding period are often set too optimistically.

Figure 6 presents our results on the Start-ups' ability to ship/deliver products in a timely manner, according to their initial promises to backers. On average, the products were delayed by 6 months. Interviewees mentioned various causes of delays, the majority of which were due to 'unknown unknowns', which were discovered in the later phases of the development processes or even while initiating series manufacture.

While some of the issues resulting in delays are related to lack of insights on sourcing of the components, on distribution channels and the various certifications that are required by different countries; the others are core technical design and product development issues. For instance, start-up (4) mentioned that the polymer used for injection molding in their first batch of production was slightly more translucent than the polymer that were used during prototyping. This variation led to unforeseen measurement faults in the product, which required late design changes on the utilized photo-interrupter sensors in their product.

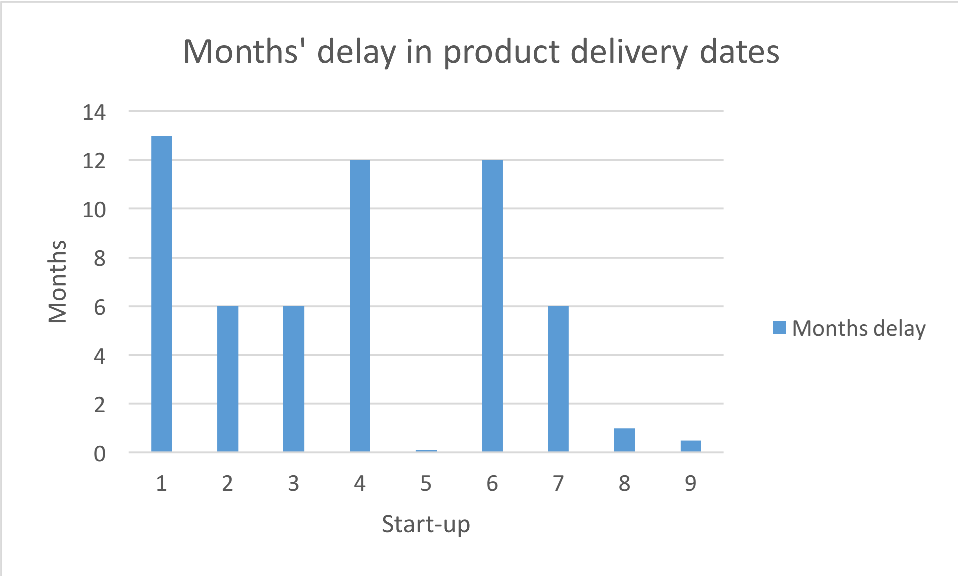



Figure 6 Overview of how the products promised in the crowdfunding campaigns in some cases have been delayed. For start-up (1) the product is sold to a manufacturing company and has not yet been delivered 13 months after initial deadline

*'Professional Business Backers'*

To laymen, a crowdfunding platform offers the opportunity to support a palette of different campaigns in return for rewards. Our study finds that the platforms are also utilized by industry professionals, as an entry point for potential new business opportunities. This became evident as all interviewees expressed that, during the campaign, they were approached directly by manufacturers offering their services. Start-Up (1) explained that they on a daily basis experienced offerings of manufacturing or design consultancy. None of these were pursued however, and it was argued for example "It is clear that people in the manufacturing eco-system are scouting the crowdfunding platforms. We however found it difficult to assess the quality and integrity of those offerings and chose not to settle deals with any of them." Start-Up (1).

Seven of the campaigns, excluding campaigns (2) and (4), were further approached by distribution companies interested in retail partnerships. Start-up (3) described that it had established a partnership with one of these companies on distribution for all sales of their product in Asia.

The last characteristic of crowdfunded product development highlighted in this study is therefore how crowdfunding is not only an opportunity to collect presales through the backers. It is also a potential for broader marketing of company and product providing potential partnerships with "professional business backers" on manufacturing, design consultancy, distribution and retail after the campaign.

# *Discussion*

Through this study we set out to provide a deeper understanding of crowdfunded product development. The following sections provide a discussion of our findings, in terms of the characteristics of crowdfunded product development, team compositions and the adoption of design methodologies.

## ***Characteristics of crowdfunded product development***

### *Variation in design maturity levels*

The variation in perceived maturity varies significantly among the start-ups. At time of their campaigns, some of them had mature designs tested through several prototyping cycles whereas the others only had early proof-of-concept prototypes that were far from manufacturing-ready prototypes (Figure 4). This finding introduces new questions: Do campaigns with a low design maturity become less successful? Do they get delayed significantly or tend to have a different approach to design methodologies? Our data do not provide clear answers to these questions, but there are still some indications for further investigations; for instance, a closer look at the data from start-ups (1), (4) and (6) show that low design maturity might result in long delays.

### *Leveraging external investment*

Recent developments have changed the ease of access to digital manufacturing tools (Jensen et al., 2016b), collective design platforms (Özkil, 2017) and physical facilities in FabLabs and Makerspaces (Gershenfeld, 2008). Together, these new offerings provide an interlacing foundation of infrastructure that can support inventors and entrepreneurs in prototyping and incubation of designs. Crowdfunding further extends this infrastructure to the business domain, as it changes 'what gets made and who has the opportunity to make it' (Yulman et al., 2017). Accordingly, four of the startups in our study claim that they would not be able to raise funding if it was not for their crowdfunding success.

Furthermore, the majority of the campaigns in our study, - all but one - received external funding from investors upon the successful completion of their crowdfunding campaigns. We believe that, crowdfunding success inherently validates the market potential of a product, which subsequently attracts the external investors and might be developing into a 'need to have' market validation.

### *Co-creation and Community Feedback*

The opportunity to receive early and continuous feedback from users, and possibilities for collaborative design and co-creation has always been highlighted features of crowdfunding (Gerber et al., 2012), (Stanko and Henard, 2016). Similarly, the majority of the participants of our study also acknowledge the potential for creating dynamic dialogs with the campaign backers. However, when they were asked if they have utilized the feedback they received from their backers; only a single team gave a positive answer.

This significant difference between what is expected and what is observed in reality warrants further investigation. One of the founders (start-up 1) describes the conscious choice for deprioritizing dialogue with backers through the following quote: "Some backers in crowdfunding have lead-user characteristics. These people can provide valuable insights but are also very demanding. They do not hesitate to articulate frustration if their ideas are not met - this makes such dialogue challenging and time consuming. Besides lead-users the clear majority of backers provide suggestions which are simply trivial or too highflying to ever be pursued." This finding is supported by a recent case study by Scaringella, who discusses the value of customer involvement in product development for start-ups. It is highlighted how feedback from ostensible customers can be out of scope and misleading (Scaringella, 2017). Einstein takes this reasoning a step forward, and claims that backer involvement can actually increase risks of campaigns to fail (Einstein, 2015). He further argues that crowdfunding dynamics cannot substitute practicing user oriented design in the early phases of the development process; and the feedback provided during a campaign might very well provide insights - but it is a point in time where it is too late to make design changes.

### *Slipping deadlines*

In a study by Mollick it is shown that over 75% of crowdfunding campaigns initiators on Kickstarter couldn't deliver promised rewards to backers on time (Mollick, 2014b). Delays in product development are not unique for crowdfunding, and how to avoid delays have been a topic of ongoing interest (Thomke and Reinertsen, 2012).
In this study, three campaigns – (5), (8) and (9) – managed to deliver their products to their backers on time, but on average campaigns were delayed by six months. According to the campaign initiators, the deadlines were not set unrealistically on purpose, but their general lack of experience to handle the unforeseen challenges, combined with the desire for presenting an attractive delivery date to backers, were the main reasons for the delays.

### *'Professional business backers'*

The fact that crowdfunding platforms are being screened by industry professionals in the search for new potential business is not surprising, but to our knowledge such dynamics of crowdfunding have not previously been documented in research. The CEO of start-up (8) elaborated his view on this development with the following quote: "The factories in China are getting more progressive, as competition is intensifying. They are willing to engage with start-ups early in product development, and minimum order quantities are lowered [compared to a few years back] allowing for 'high mix low volume' production – because they can see the potential for large orders in the future." These developments –in many ways – can be considered as advantages for start-ups that target crowdfunded product development but navigating through the process of selecting manufacturing partners is still a challenge as expressed by the participants of our study.

## *How teams in crowdfunded product development are composed?*
Among the different aspects of team compositions that are documented in the previous sections, 'experience' stands out as the most important indicator for whether teams can deliver on time. While the average delay is 6.3 months for all campaigns, teams with experienced members were only delayed by on average 0.5 months (Figure 2, Figure 6). Previous studies also confirm that two of the strongest drivers of project timeliness were related to strong team competencies and composition and solid predevelopment activities including prototyping (Cooper and Kleinschmidt, 1994).

The two teams, team (2) and team (8), distinguish themselves from the rest; in terms of their educational background (Figure 3), previous start-up activities (Figure 2) and knowledge on design methodology (table 2). Despite their relatively low experience, they chose to develop their projects to a perceived design maturity level of 80% before launching the campaigns, whereas the remaining teams chose much lower design maturity of 50% or lower. Both teams argued that a high maturity state was necessary in order to prove the concepts realizations, due to the team's evaluations of the overall feasibility.

## *Which design methodologies are known and used in the design process?*
Table 2 highlights that the startups that participated in our study have a limited knowledge and experience with design methodologies. It is also visible that the team compositions, as presented in Figure 3, have a significant effect, as the number of engineers in a development team correlates with the number of methodologies that are known to those teams. In combination, Table 2 illustrate that it is often a conscious choice not to utilize existing knowledge on design methodologies. Here the lack of flexibility and an expected burden of documentation were stressed as the primary reasons. Furthermore, these arguments aligns well with the previous studies on the general lack of appeal for the adoption of methodologies. (Bylund et al., 2003) and (Araujo et al., 2001).

The most widely adopted methodologies, The Lean Start-up and the Business Model Canvas are exceptions though, and are also adapted by teams without engineers. Participants argued that these methodologies have been recommended by respected colleagues and they are commonly used by their peers in the start-up community. Furthermore, it is also claimed that both methodologies are presented in an appealing format with a suitable level of generalizability. In contrast, one of the participants has pointed out that they disregarded the other methods they knew because they create a discomfort due to their 'academic' way of prescribing their use.

Agile Development and SCRUM are also relatively well known methodologies among the participants and a number of teams use a Kanban based tool for overall project management. Despite the fact that it originates from the automotive industry (Johnson, 2017), Kanban has been adopted as an important tool to utilize Agile or SCRUM methodologies in software development in the recent years (Nakazawa and Tanaka, 2015).

Three participants in our study (1, 3 and 4) argued that Agile Development and SCRUM are not fully suitable for the development of their mechanical or electro-mechanical products. A similar argumentation is presented in (Hostettler et al., 2017), where the authors claim that SCRUM assumes a product owner with full clarity on the final product layout; and this does not reflect the reality of physical product development where the 'problem' and the 'solution' coevolves.

The list of methodologies used for the interviews of this study were primarily established from the compiled list presented in the work of (Stock and Seliger, 2016). A limitation for this approach is that the list is not exhaustive – despite the interviewees being opted to propose additional methodologies of their choice - and further, varying viewpoints might exist on how the different support should be characterized as respectively methodologies, methods, principles or tools. Lastly, it can be argued that the has a main focus on work originating in German speaking countries and might not be globally disseminated.

### *Prototypes in the design process*
Two start-ups (2) and (5) mentioned that their design processes were very prototyping focused. We find that these statements follow a current trend in design research, where there is a growing body of research focused on the importance and role of prototyping in product development (Deininger et al., 2017), (Camburn et al., 2017). (Christie et al., 2012) argues that a need exists for more dedicated prototyping strategies. (Jensen et al., 2017) stresses the importance of 'prototrialing' to elicit 'unknown unknowns' factors, (Menold et al., 2017) proposes a prototype for X framework, and (Camburn et al., 2013) proposes a prototyping framework for conceptual stages of design. Our study also shows that the teams have extensively prototyped during their campaigns; for both divergent and convergent

purposes (Jensen et al., 2016a). Besides design specific outcomes, it was reported that prototypes were utilized as a medium for communication within the teams. This to a level that exceeds what would be categorized as prototypes as boundary objects (Subrahmanian et al., 2003) and have more characteristics of prototypes as documentations tools or a physical version control system (Schmidt, 2018). The majority of the teams claim that their tests, insights and challenges in the product development processes were not necessarily documented, but instead they were communicated through conversations taking place around the prototypes. In this way, some of the teams have been using their prototypes as carriers of knowledge on the newest version of product and design changes. This in preference to the use of written documentation and specifications.

# *Conclusion*

This paper presents a study of hardware start-ups and crowdfunded product development; with a particular focus on the characteristics of crowdfunded product development, how the start-up teams are composed and which design methodologies are known and used in the design process.

The study includes interviews with 9 hardware start-ups that have gone through a crowdfunding campaign and the results of the study documents our findings in respect to the research questions of the study. The first part of the study is focused on the composition of the design teams. We document different aspects of the team compositions and present that inexperienced entrepreneurs can enter the crowdfunding domain, but also that the presence of experienced team members has a positive influence on the team's ability to timely deliver the promised products to the campaign backers. The second part is focused on the teams' use of design methodology. We present findings on the teams' prior knowledge on design methodologies and document that only very a limited adoption of methodology takes place for the crowdfunding projects. Finally, we outline five characteristics for crowdfunded product development. These concern different aspects of product development and the dynamics of the crowdfunding paradigm, which in different ways have influenced the start-up teams.

The results of the study not only provide empirical insights on crowdfunded product development. They can also be considered as design implications or be used as probes for further exploration exploitation. How could crowdfunding platforms to a greater extent than at present include mechanisms to support and structure dialogue between campaign creators and backers is one example. Also, our study identifies large variations in the design maturity levels of the campaigns and the delays of the campaigns respectively. To establish a better understanding of the strategic decisions behind the chosen design maturity and the causes for delays are opportunities for further work. This includes how these parameters might be are connected and differentiated over different product categories or geographical regions and cultures. Finally, we encourage further exploration of the prototyping practices of hardware start-ups to better understand their role in entrepreneurial development practices.

## *Disclosure Statements*

No potential conflict of interest was reported by the authors.

## *Funding*

No external funding sources funded the work presented in this paper.

# *References*

Agrawal, A.K., Catalini, C., Goldfarb, A., 2013. Some simple economics of crowdfunding. National Bureau of Economic Research.
Albers, A., Braun, A., 2011. Der Prozess der Produktentstehung. Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hrsg.: F. Henning.
Andreasen, M.M., 2011. 45 Years with design methodology. Journal of Engineering Design 22, 293–332.
Araujo, C.S. de jr, Technical University of Denmark, Department of Mechanical Engineering, DTU, 2001. Acquisition of product development tools in industry: A theoretical contribution. Lyngby,.
Argyris, C., 1997. Organizational Learning: A Theory of Action Perspective. Reis 345. https://doi.org/10.2307/40183951
Bannerman, S., 2013. Crowdfunding culture. Wi: Journal of Mobile Media 7.
Belleflamme, P., Lambert, T., Schwienbacher, A., 2014. Crowdfunding: Tapping the right crowd. Journal of Business Venturing 29, 585–609.
Berthon, P.R., Pitt, L.F., McCarthy, I., Kates, S.M., 2007. When customers get clever: Managerial approaches to dealing with creative consumers. Business Horizons 50, 39–47.
Birkhofer, H., 2001. Product development as a structured and interactive network of knowledge - A revolutionary approach. Design Applications in Industry and Education 457–464.
Blank, S., 2013. Why the lean start-up changes everything. Harvard business review 91, 63–72.
Blank, S., 2012. The startup owner's manual: The step-by-step guide for building a great company. BookBaby.
Blessing, L.T.M., Chakrabarti, A., Wallace, K.M., 1998. An overview of descriptive studies in relation to a general design research methodology, in: Designers. Springer, pp. 42–56.
Böhmer, A., Grauvogl, C., Schweigert, S., Becerril, L., Devecka, J., Bahrouni, Z., Lindemann, U., 2017a. Towards Agile Development of Physical Products.
Böhmer, A., Hugger, P., Lindemann, U., 2017b. Scrum within Hardware Development.
Booker, J., 2012. A survey-based methodology for prioritising the industrial implementation qualities of design tools. Journal of Engineering Design 23, 507–525.
Brockman, B.K., 2003. The role of existing knowledge in new product innovativeness and performance. Decision Sciences 34, 385–419. https://doi.org/10.1111/1540-5915.02326
Brown, T., 2009. Change by design.
Bylund, N., Grante, C., López-Mesa, B., 2003. Usability in industry of methods from design research, in: DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm.
Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., Wood, K., 2017. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Design Science 3.
Camburn, B.A., Dunlap, B.U., Kuhr, R., Viswanathan, V.K., Linsey, J.S., Jensen, D.D., Crawford, R.H., Otto, K., Wood, K.L., 2013. Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment V005T06A033. https://doi.org/10.1115/DETC2013-13072
Chakrabarti, A., Lindemann, U., 2015. Impact of Design Research on Industrial Practice: Tools, Technology, and Training. Springer.
Chang, D., Lee, C., 2018. A product affective properties identification approach based on web mining in a crowdsourcing environment. Journal of Engineering Design 0, 1–35. https://doi.org/10.1080/09544828.2018.1463514
Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L., Crawford, R.H., 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables, in: American Society for Engineering Education. American Society for Engineering Education.
Cooper, R.G., 1990. Stage-gate systems: a new tool for managing new products. Business horizons 33, 44–54.
Cooper, R.G., Kleinschmidt, E.J., 1994. Determinants of timeliness in product development. Journal of Product Innovation Management 11, 381–396.
Day, G.S., 2007. Is it real? Can we win? Is it worth doing. Harvard business review 85, 110–120.
Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., 2017. Novice designers' use of prototypes in engineering design. Design Studies 51, 25–65. https://doi.org/10.1016/j.destud.2017.04.002
Du, Q., Fan, W., Qiao, Z., Wang, G., Zhang, X., Zhou, M., 2015. Money talks: A predictive model on crowdfunding success using project description.
Eastman, C.M., 2012. Design for X: concurrent engineering imperatives. Springer Science & Business Media.
Eder, W.E., 1998. Design modeling-a design science approach (and Why does industry Not Use It?). Journal of Engineering Design 9, 355–371.
Ehrlenspiel, K., Meerkamm, H., 2013. Integrierte produktentwicklung: Denkabläufe, methodeneinsatz, zusammenarbeit. Carl Hanser Verlag GmbH Co KG.
Eigner, M., Roubanov, D., Zafirov, R., 2014. Modellbasierte virtuelle Produktentwicklung. Springer.

Einstein, B., 2015. Kickstarter != Product/Market Fit [WWW Document]. Bolt Blog. URL https://blog.bolt.io/kickstarter-product-market-fit-95f2b13ae75f#.dy6ji1231 (accessed 11.22.16).
Eisenhardt, K.M., 1989. Building theories from case study research. Academy of management review 14, 532–550.
Forbes, H., Schaefer, D., 2017. Social Product Development: The Democratization of Design, Manufacture and Innovation. Procedia CIRP 60, 404–409.
Frederiksen, D.L., Brem, A., 2017. How do entrepreneurs think they create value? A scientific reflection of Eric Ries' Lean Startup approach. Int Entrep Manag J 13, 169–189. https://doi.org/10.1007/s11365-016-0411-x
Gassmann, O., Frankenberger, K., Csik, M., 2013. The St. Gallen business model navigator.
Gerber, E.M., Hui, J.S., Kuo, P.-Y., 2012. Crowdfunding: Why people are motivated to post and fund projects on crowdfunding platforms, in: Proceedings of the International Workshop on Design, Influence, and Social Technologies: Techniques, Impacts and Ethics.
Gershenfeld, N., 2008. Fab: the coming revolution on your desktop–from personal computers to personal fabrication. Basic Books.
Graner, M., 2016. Are methods the key to product development success? An empirical analysis of method application in new product development, in: Impact of Design Research on Industrial Practice. Springer, pp. 23–43.
Greenberg, M.D., Easterday, M.W., Gerber, E.M., 2015. Critiki: A scaffolded approach to gathering design feedback from paid crowdworkers, in: Proceedings of the 2015 ACM SIGCHI Conference on Creativity and Cognition. ACM, pp. 235–244.
Greenberg, M.D., Pardo, B., Hariharan, K., Gerber, E., 2013. Crowdfunding support tools: predicting success & failure, in: CHI'13 Extended Abstracts on Human Factors in Computing Systems. ACM, pp. 1815–1820.
Hemer, J., 2011. A snapshot on crowdfunding. ISI.
Herrmann, J.W., Cooper, J., Gupta, S.K., Hayes, C.C., Ishii, K., Kazmer, D., Sandborn, P.A., Wood, W.H., 2004. New directions in design for manufacturing, in: ASME 2004 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, pp. 853–861.
Hoppmann, J., Rebentisch, E., Dombrowski, U., Zahn, T., 2011. A framework for organizing lean product development. Engineering Management Journal 23, 3–15.
Hostettler, R., Böhmer, A., lindemann, udo, knoll, alois, 2017. TAF Agile Framework.
Hu, M., Li, X., Shi, M., 2015. Product and pricing decisions in crowdfunding. Marketing Science 34, 331–345.
Hui, J.S., Gerber, E., Greenberg, M., 2012. Easy money? The demands of crowdfunding work. Northwestern University, Segal Design Institute 1–11.
Indiegogo: Crowdfund Innovations & Buy Unique Products [WWW Document], 2018. . Indiegogo.com. URL https://www.indiegogo.com/ (accessed 6.29.18).
Jensen, L.S., Özkil, A.G., Mortensen, N.H., 2016a. Prototypes in engineering design: Definitions and strategies, in: DS 84: Proceedings of the DESIGN 2016 14th International Design Conference.
Jensen, L.S., Özkil, A.G., Mougaard, K., 2016b. Makerspaces in Engineering Education: A Case Study V003T04A003. https://doi.org/10.1115/DETC2016-60066
Jensen, M.B., Elverum, C.W., Steinert, M., 2017. Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures. Design Studies 49, 1–31. https://doi.org/10.1016/j.destud.2016.12.002
Johnson, H.A., 2017. Trello. J Med Libr Assoc 105, 209–211. https://doi.org/10.5195/jmla.2016.49
Kichuk, S.L., Wiesner, W.H., 1997. The big five personality factors and team performance: implications for selecting successful product design teams. Journal of Engineering and Technology Management 14, 195–221. https://doi.org/10.1016/S0923-4748(97)00010-6
Kickstarter Stats [WWW Document], 2017. URL https://www.kickstarter.com/help/stats?ref=footer (accessed 11.6.17).
Kickstarter [WWW Document], 2018. . Kickstarter.com. URL https://www.kickstarter.com/ (accessed 6.29.18).
Kickstarter.com [WWW Document], 2016. . www.kickstarter.com. URL https://www.kickstarter.com/help/stats?ref=foote (accessed 11.21.16).
Koch, J.-A., Siering, M., 2015. Crowdfunding success factors: The characteristics of successfully funded projects on crowdfunding platforms.
Kuppuswamy, V., Bayus, B.L., 2015. Crowdfunding Creative Ideas: The Dynamics of Project Backers in Kickstarter (SSRN Scholarly Paper No. ID 2234765). Social Science Research Network, Rochester, NY.
Lindemann, U., 2005. Udo Lindemann Methodische Entwicklung technischer Produkte.
Manifesto for Agile Software Development [WWW Document], 2001. URL http://agilemanifesto.org/ (accessed 11.28.17).
Martínez-Climent, C., Zorio-Grima, A., Ribeiro-Soriano, D., 2018. Financial return crowdfunding: literature review and bibliometric analysis. Int Entrep Manag J 1–27. https://doi.org/10.1007/s11365-018-0511-x
Massolution, 2015. 2015CF Crowdfunding Industry Report [WWW Document]. URL http://reports.crowdsourcing.org/?route=product/product&product_id=54 (accessed 11.21.16).

Menold, J., Jablokow, K., Simpson, T., 2017. Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. Design Studies 50, 70–112. https://doi.org/10.1016/j.destud.2017.03.001
Mollick, E., 2015. Delivery Rates on Kickstarter. Available at SSRN.
Mollick, E., 2014a. The dynamics of crowdfunding: An exploratory study. Journal of Business Venturing 29, 1–16. https://doi.org/10.1016/j.jbusvent.2013.06.005
Mollick, E., 2014b. The dynamics of crowdfunding: An exploratory study. Journal of Business Venturing 29, 1–16. https://doi.org/10.1016/j.jbusvent.2013.06.005
Moorman, C., Miner, A.S., 1997. The impact of organizational memory on new product performance and creativity. Journal of marketing research 91–106.
Müller, R.M., Thoring, K., 2012. Design thinking vs. lean startup: A comparison of two user-driven innovation strategies. Leading Through Design 151.
Nakazawa, S., Tanaka, T., 2015. Prototype of Kanban Tool and Preliminary Evaluation of Visualizing Method for Task Assignment, in: Computer Application Technologies (CCATS), 2015 International Conference On. IEEE, pp. 48–49.
Nattermann, R., Anderl, R., 2013. The W-Model – Using Systems Engineering for Adaptronics. Procedia Computer Science, 2013 Conference on Systems Engineering Research 16, 937–946. https://doi.org/10.1016/j.procs.2013.01.098
Osterwalder, A., Pigneur, Y., 2010. Business model generation: a handbook for visionaries, game changers, and challengers. John Wiley & Sons.
Özkil, A.G., 2017. Collective design in 3D printing: A large scale empirical study of designs, designers and evolution. Design Studies 51, 66–89. https://doi.org/10.1016/j.destud.2017.04.004
Pahl, G., Beitz, W., 2013. Engineering Design: A Systematic Approach. Springer Science & Business Media.
Panchal, J.H., 2015. Using Crowds in Engineering Design–Towards a Holistic Framework, in: 2015 International Conference on Engineering Design, Design Society, Milan, Italy, July. pp. 27–30.
Paternoster, N., 2014. Software development in startup companies: A systematic mapping study. Information and Software Technology 56, 1200–1218. https://doi.org/10.1016/j.infsof.2014.04.014
Ponn, J., Lindemann, U., 2011. Konzeptentwicklung und Gestaltung technischer Produkte: systematisch von Anforderungen zu Konzepten und Gestaltlösungen. Springer-Verlag.
Pyatt, G., 1966. Human Capital: A Theoretical and Empirical Analysis, with Special Reference to Education. Economic Journal 76, 635. https://doi.org/10.2307/2229541
Rajaeian, M.M., Cater-Steel, A., Lane, M., 2018. Determinants of effective knowledge transfer from academic researchers to industry practitioners. Journal of Engineering and Technology Management 47, 37–52. https://doi.org/10.1016/j.jengtecman.2017.12.003
Ries, E., 2011. The Lean Startup: How Today's Entrepreneurs Use Continuous Innovation to Create Radically Successful Businesses. Random House LLC.
Rijnsoever, F.J.V., Weele, M.A.V., Eveleens, C.P., 2017. Network brokers or hit makers? Analyzing the influence of incubation on start-up investments. Int Entrep Manag J 13, 605–629. https://doi.org/10.1007/s11365-016-0416-5
Royce, W.W., 1987. Managing the development of large software systems: concepts and techniques, in: Proceedings of the 9th International Conference on Software Engineering. IEEE Computer Society Press, pp. 328–338.
Scaringella, L., 2017. Involvement of "Ostensible Customers" in really new innovation: Failure of a start-up. Journal of Engineering and Technology Management 43, 1–18. https://doi.org/10.1016/j.jengtecman.2016.11.001
Schmidt, T.S., 2018. Set-based Design in Agile Development: Reinterpreting the Repository Tree, in: International Conference on Engineering, Technology and Innvoation. Presented at the International Conference on Engineering, Technology and Innvoation, Stuttgart.
Schmitt, S.O., Scheitza, M., Groche, P., 2015. A model for improving the applicability of design methodologies to mechanical engineering design routines. Journal of Engineering Design 26, 302–320. https://doi.org/10.1080/09544828.2015.1048198
Song, C., Luo, J., Hölttä-Otto, K., Otto, K., Seering, W., 2015. The Design of Crowd-Funded Products, in: ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V007T06A040–V007T06A040.
Stanko, M.A., Henard, D.H., 2017. Toward a better understanding of crowdfunding, openness and the consequences for innovation. Research Policy 46, 784–798.
Stanko, M.A., Henard, D.H., 2016. How crowdfunding influences innovation. MIT Sloan Management Review 57, 15.
Stock, T., Seliger, G., 2016. Methodology for the Development of Hardware Startups. Advanced Materials Research 1140, 505–512. https://doi.org/10.4028/www.scientific.net/AMR.1140.505
Subrahmanian, E., Monarch, I., Konda, S., Granger, H., Milliken, R., Westerberg, A., Group, T., 2003. Boundary Objects and Prototypes at the Interfaces of Engineering Design. Computer Supported Cooperative Work (CSCW) 12, 185–203. https://doi.org/10.1023/A:1023976111188
Suh, N.P., 1998. Axiomatic design theory for systems. Research in engineering design 10, 189–209.

Takeuchi, H., Nonaka, I., 1986. New New Product Development Game [WWW Document]. URL https://hbr.org/product/new-new-product-development-game/86116-PDF-ENG (accessed 11.28.17).
Thomke, S., Reinertsen, D., 2012. Six Myths of Product Development [WWW Document]. Harvard Business Review. URL https://hbr.org/2012/05/six-myths-of-product-development (accessed 7.5.17).
Vajna, S., Weber, C., Bley, H., 2009. Integrated Design Engineering - Ein interdisziplinäres Modell. Springer.
VDI-Fachbereich Produktentwicklung und Mechatronik: VDI 2206 – Entwicklungsmethodik für mechatronische Systeme, 2004. . VDI-Fachbereich.
VDI-Fachbereich Produktentwicklung und Mechatronik: VDI 2221 – Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte., 1993.
Von Hippel, E., 1986. Lead users: a source of novel product concepts. Management science 32, 791–805.
Weber, E., Jung, S., 2015. The Influence of Prior Experience on Innovativeness of Startup Business Ideas.
Wright, M., Hmieleski, K.M., Siegel, D.S., Ensley, M.D., 2007. The role of human capital in technological entrepreneurship. Entrepreneurship Theory and Practice 31, 791–806.
Xu, A., Yang, X., Rao, H., Fu, W.-T., Huang, S.-W., Bailey, B.P., 2014. Show me the money!: an analysis of project updates during crowdfunding campaigns, in: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems. ACM, pp. 591–600.
Yeh, T.-M., Pai, F.-Y., Yang, C.-C., 2010. Performance improvement in new product development with effective tools and techniques adoption for high-tech industries. Quality & Quantity 44, 131–152.
Yulman, N., Terra, J., Dunham, Z., Gallagher, D., 2017. Why Hardware Studio? | Hardware Studio [WWW Document]. URL https://hardware.studio/articles/why-hardware-studio (accessed 10.20.17).

INTERNATIONAL DESIGN CONFERENCE - DESIGN 2018
https://doi.org/10.21278/idc.2018.0415

# PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT

L. S. Jensen, L. Nissen, N. Bilde and A. G. Özkil

## Abstract

This paper provides a study of prototyping; with the aim of understanding how the fidelity of prototypes affects inputs by users. During development of a mechatronic padlock, 4 physical prototypes at varying fidelity were fabricated. 66 interviews with users were conducted. Users were presented with 1 of the 4 prototypes. The study finds; fidelity of prototypes affects users' feedback. Though not linearly and without unambiguity. This underlining the complexity of prototyping. A better understanding of how prototypes are perceived can help designers in establishing prototyping strategies.

*Keywords: prototyping, prototyping strategies, engineering design, product design*

## 1. Introduction

Prototypes are essential in product development and it is generally accepted that designers utilize prototypes in various ways and formats throughout the design process.

Historically, the costs associated with prototyping accounted for as much as 50% of the costs in product development (Cooper, 2001). In recent years we have witnessed vastly declining expenses for the tools to conduct cost effective and functional prototyping. This is substantiated by Camburn's statement: "additive manufacturing (3D printing), open-source software repositories, and reconfigurable electronic hardware enable a drastic cost reduction in single unit manufacturing" (Camburn et al., 2017). In other words; the costs and 'barrier of entry' for prototyping in product development is lowering for e.g. the development of mechatronic consumer hardware. Such opportunities introduce new questions on what defines best practice in when, how and what to prototype. Essentially, answers to such questions require designers to carefully establish prototyping strategies (Drezner, 1992; Christie et al., 2012) and plan what should be explored and learned from prototyping.

A general key objective of prototyping is to obtain sufficient knowledge on how to progress in a project with minimal expenditure in terms of time and cost (Otto and Wood, 2003). In e.g. user-centered design, prototypes are presented to relevant stakeholders to explore human factors in design. Often such prototypes do not resemble the full functionality or quality of the final product. In these situations, abstractions of prototypes can influence how the concept is communicated and stakeholders can make unintended judgements of the concept (Crilly et al., 2004). In this way, the 'quality' of prototypes influence the feedback stakeholders provide (Deininger et al., 2017). Currently, only a fragmented understanding of the fundamental question "What does prototypes prototype?" (Houde and Hill, 1997) is documented in engineering design literature.

This paper aims to contribute to the understanding of how prototype fidelity levels affect user feedback. It is our hope that insights from this study can be applied by designers when establishing prototyping strategies in product development projects. Therefore, this study is focused on the following research question:

- RQ1: How the fidelity of prototypes (representing a mechatronic concept) affect test users' perception of a concept?

Our findings are based on interviews with 66 test users of a mechatronic padlock. All test users were exposed to one of four different prototypes of the padlock design. The four prototypes all vary in their fidelity but represent the same product interfaces. All test users were interviewed in a semi-structured format by following an interview protocol with particular focus on the utility, usability and desirability of the mechatronic padlock. A comparison of these results leads to our conclusions on the influence which fidelities of prototypes have on the test-user feedback, which can be seen as recommendations in the establishment of prototyping strategies.

## 2. Background

A prototype is an artefact that approximates a feature (or multiple features) of a product, service, or system (Otto and Wood, 2003) and a large body of research supports the positive influences of prototypes in design activities (Wall et al., 1992; Schrage, 2010). Prototypes and prototyping is an integrated part of design activities and a range of different objectives, characteristics and purposes of prototyping is documented to take place in the various stages of product development (Jensen et al., 2016).

A current research trend is stressing the need for designers and industry practitioners to actively use prototypes as a key part of the product development process. (Menold, 2017) has proposed the 'Prototype for X framework' to support structured prototyping activities, (Hostettler et al., 2017) have proposed the 'TAF Agile Framework', where prototyping is a key activity for crystalizing knowledge fast throughout design teams, (Jensen et al., 2017) propose that organizations adapt a mindset to reflect a 'prototrialing' culture to effectively elicit unknown unknowns. A shared characteristic for this new research trend is that designers and practitioners are to establish prototyping strategies as part of the development process (Christie et al., 2012; Camburn et al., 2017; Lauff et al., 2017).

A prerequisite for establishing well-founded strategies on prototypes is that designers either possess (e.g. through experience) or have access to a knowledge base on various aspects of prototyping to provide adequate guidance for decision-making and execution of the strategic elements of prototyping. (Camburn et al., 2013) have proposed how these strategic aspects of prototyping can be described in the five overall categories: Scale, Integration, Logistics, Embodiment and Evaluation (Camburn et al., 2013).

$, we only have a fragmented understanding of what defines best practice in prototyping for each of the five categories proposed by Camburn. On the overall level, we know that prototyping can be a helpful tool to reduce design complexity (Gerber, 2009) and that experienced designers rely heavily on prototypes to quickly test ideas and to generate new ones. It is also widely accepted that testing with end-users is important for the viability and usability aspects of design as it leads to early identification of any problems (Heaton, 1992; Bailey and Konstan, 2003). However, it is not unambiguous how prototyping with end-user should be conducted;

(Lim et al., 2006) argues that when using low fidelity prototyping techniques, it becomes harder to claim whether the evaluation findings originate in the actual concept of the system or in the innate characteristics of the prototype (Lim et al., 2006). In Studies by (Sauer and Sonderegger, 2009; Sonderegger and Sauer, 2010), it is documented how stakeholders' evaluation of the functionality of a design was related to the design aesthetics of a prototype (Sauer and Sonderegger, 2009; Sonderegger and Sauer, 2010). Similar findings are documented in a recent and related study by (Deininger et al., 2017). In contrast, (Reid et al., 2013) find that in some cases, product representation did not influence preferences of end-users whereas in other cases it did (Reid et al., 2013).

As expressed by (Camburn et al., 2017), there is a need for establishing "a clearer understanding of quantified information gained from a prototype" and for clarifying "the effect of fidelity on consumer emotional preference". In order to further explore such lack of clarity, we conducted this study with a focus on various prototype formats and how they were perceived by potential end-users. This differs

from previous work by (i) Exclusively focusing on physical prototypes. (ii) Focusing on a mechatronic product testing and end-consumers' perception thereof. (iii) Utilization of recent advancements in 'prototyping tools' such as laser cutting, 3d printing and reconfigurable electronic hardware for the fabrication of prototypes.
The rest of the paper is organized as follows; The following section describes our methodology and describes how the data is collected and handled. Next, we present our findings based on our analysis of the data corpus which is then followed by a discussion of the results. Finally, we conclude the paper with our reflections and provide directions for future research.

## 3. Methodology

This study was conducted as part of a product development project of a mechatronic padlock. The product is being designed by a small start-up company. It is the ambition of the start-up to sell the final padlock to institutions that offer locker room access to their users. Three examples could be educational institutions, sport facilities and libraries. During the conceptual stage of the development project designers from the start-up collected feedback from test users by utilizing four different prototypes at different stages of fidelity. The prototypes are presented in (Figure 1), and only one prototype was presented to each participant. We believe that two primary reasons make the mechatronic padlock suitable for this study. (i) The basic concept of a padlock is considered known by the general public. (ii) The code-input interface for this padlock concept is not widely domesticated and hereby suitable for a usability study. In order to collect insights and feedback, semi-structured interviews were conducted by following an interview protocol.

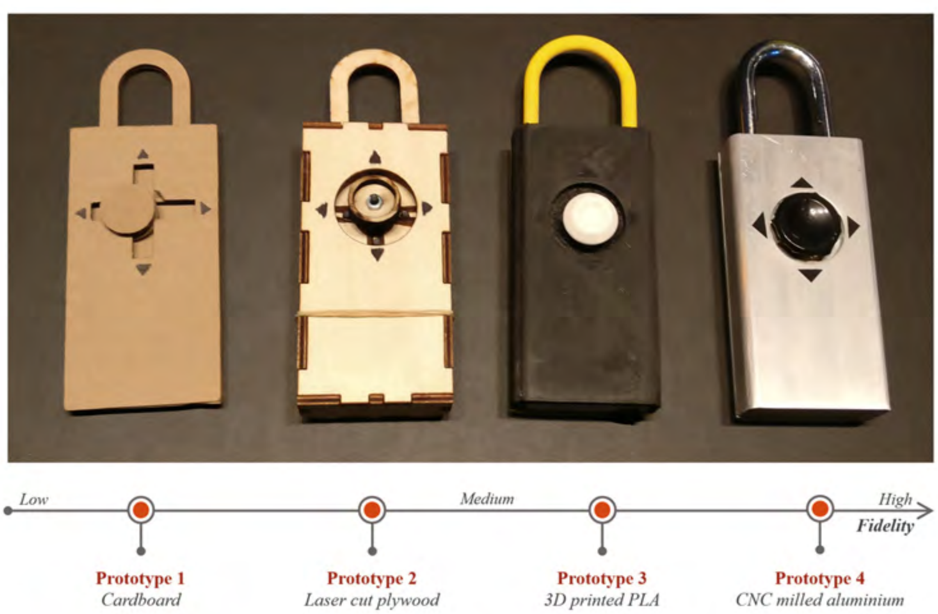



**Figure 1. Photograph of the four prototypes of the padlock design used for the study; The process bar in the bottom illustrates how the fidelity of the prototypes increases from left to right**

### 3.1. Participants and the mechatronic padlock

The study was conducted with a total of 66 participants heterogeneously distributed throughout different social parameters. The participants varied from 13 to 48 years of age and the division of gender was 34 males and 32 females. All participants represent the target group for the mechatronic padlock, as they are frequent users of one more of the three facilities; educational institutions, sport facilities or libraries where there currently are locker rooms available to the users.

## 3.2. Interview protocol and focus

The interviews were conducted by an interviewer and a silent observer at the participant's respective location, e.g. at office communities and public study halls. The interview protocol used was inspired by a recent and related study by (Deininger et al., 2017): The first part of the interviews collected overall background information on the participant, the second part concerned questions to evaluate the participant's understanding of the padlock concept and the last part evaluated the perceived utility, usability and desirability by the participant.

The interview guide also consisted of three qualitative questions where participants could respond how they understood the prototype, what they liked and what they would change. Additional follow-up questions were encouraged by the interviewer. Whenever possible responses were coded directly and further comments were noted by the silent observer. Additionally, one question was based on the Microsoft Product Reaction cards, which is a dedicated card deck for usability testing (Benedek and Miner, 2002). The card deck is designed by usability researchers at Microsoft and the total deck consist of 118 words and phrases, which are considered to reflect positive, neutral and negative aspects of a product. The use of the reaction cards is documented to support users in telling a rich and revealing story on their experience (Barnum and Palmer, 2010). On the other hand, the use of the reaction cards can also introduce a bias, which should be considered as a reservation for the result of the study.

The participant was presented with a selection of 19 words, with the option to select 3 of these words.

## 3.3. Prototypes

When prototypes of different fidelity levels are compared, a measure of applicable comparison is convenient. In a case study by (Zhang et al., 2012), concept interfaces are resembled across all prototypes for comparison. Further, only some dimensions of the prototypes are varied. A similar approach is adapted for this study by maintaining the padlock concept interfaces with a directional code input on the front. Variance was only introduced in dimensions such as in materials, ergonomics, look and feel of the prototypes. All prototypes were designed and fabricated by the designers of the padlock concept with the exception of prototype 4, where the aluminum housing was CNC milled with the support of a workshop technician (Table 1).

**Table 1. Overview of time, estimated costs, tools and resources needed for the fabrication of the four prototypes**

| | Prototype 1 | Prototype 2 | Prototype 3 | Prototype 4 |
|---|---|---|---|---|
| **Time: Design & construction** | 30 minutes | 2 hours | 4 hours | 20 hours |
| **Fabrication: Estimated cost** | 1 € | 20 € | 50 € | 400 € |
| **Tools & Resources** | Cardboard<br>Scissor<br>Knife<br>Glue | Plywood<br>2 X Rubber band<br>Bolt & nut<br>CAD layout<br>Laser cutter | ABS filament<br>Button mechanism<br>Glue<br>CAD layout<br>3D printer | Shackle<br>Nylon Button<br>Input mechanism<br>PCB<br>Battery<br>Aluminum<br>CAD layout<br>3 axis CNC<br>Machine technician |

## 3.4. Data analysis

The data generated from the interviews was a combination of quantified information (answers on a Likert scale and choice of reaction cards) and qualitative information recorded by the silent observer. The data was transcribed and analyzed by two researchers with advanced degrees in engineering design and the designers from the start-up company. The quantified and directly coded data from the interviews were synthesized and visualized as presented in Figure 3 – Figure 7. The authors worked collaboratively on the coding and analysis of the qualitative aspects of the interviews in order to further comprehend the reasoning provided by the participants. As this activity were carried out as a concurrent and collaborative activity it was not possible to verify this coding through an interrater reliability evaluation. The results of such activity is presented in Figure 2.

## 4. Results

### 4.1. Utility

This first part of the interviews had the purpose of evaluating if participants understood the padlock interface concept. The comprehensions thereof are summarized in Figure 2, and they were based on the participants' ability to answer the question: "Can you explain how you would unlock the prototype?"
Prototype 1 scored the highest number of correct answers together with prototype 3, while prototype 2 and the 'high-fidelity' prototype 4 received the majority of incorrect answers. From the coded feedback from the participants, it is indicated that the slits in the cardboard of prototype 1 and the simplistic layout of prototype 3 helped the participants understand the intended use of the padlock. In interviews involving prototype 2, a group of participants (n=3) perceived that the joystick could rotate. This can be exemplified by participant 57's statement: "I would turn this wheel a bit to the left, and then a little more to the right, and then back again to hit the correct numbers" - even though no numbers were present on the prototype.

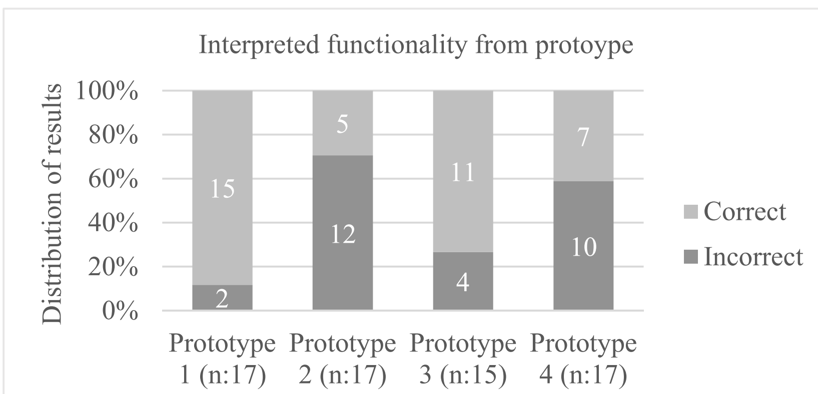



**Figure 2. Evaluation of the four prototypes in terms of their ability to communicate the working principle of the padlock concept's locking mechanism**

The incorrect answers on prototype 4 were by a group of participants (n=2) based on technological expectations. Participant 42 was expecting an app to unlock it, and participant 32 was assuming there would be a display with numbers on the product.
A frequent and equally often represented concern across all prototypes were the participants' concern about their ability to remember a directional code if they were to use it at a locker. In order for the participants to express their opinion on the prototypes, they were asked how they would evaluate the interface of the locking mechanism to work in practice. The answers were recorded on a Likert scale and are summarized in Figure 3.
Figure 3 presents how prototypes 1 and 2 receive evaluations with a lower distribution than prototypes 3 and 4. It was found that the prototype 4 in high fidelity received more concrete feedback, e.g. exemplified by Participant 39: "In a practical scenario dirt and gravel could penetrate the lock at the button." Though the coding it was concluded that examples of concrete feedback was given in 8 cases for prototype 4. Prototype 3 had the second highest level of concrete feedback with 5 cases. A hypothesis for the more concrete feedback on higher fidelity prototypes and average evaluation of the low fidelity prototypes can be the higher level of abstraction needed to interpret low fidelity prototypes.

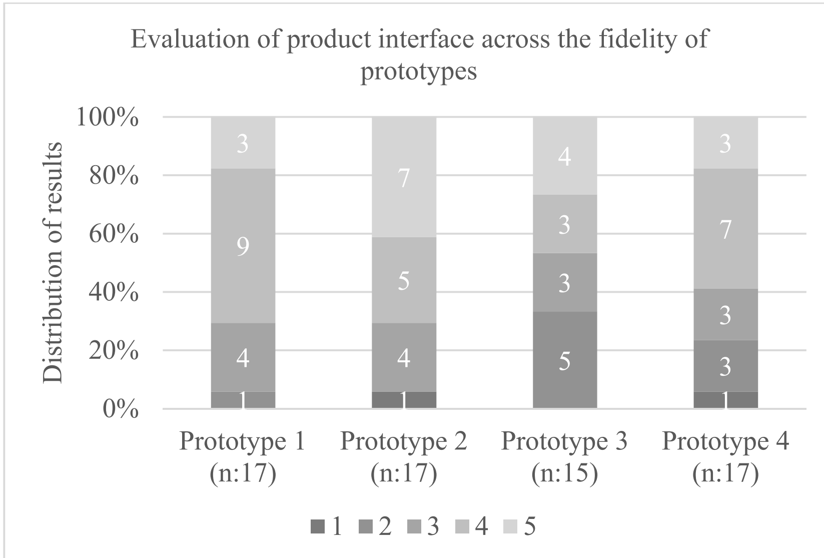



**Figure 3. Overview of the participants' evaluation of the locking mechanism of the different prototypes, where 1 is very unattractive and 5 is very attractive**

## 4.2. Usability

The second section of the results describes the participants' perceived usability of the four prototypes. Questions prompted the participants to provide their view on the usability of the padlock concept by assessing the interface of the prototype. The participants were asked about how 'easy' it was to understand the interface and how to interact with it. The participants were then asked to what extend they found the concept to be a user-friendly solution [to themselves]. The results are summarized in Figure 4.

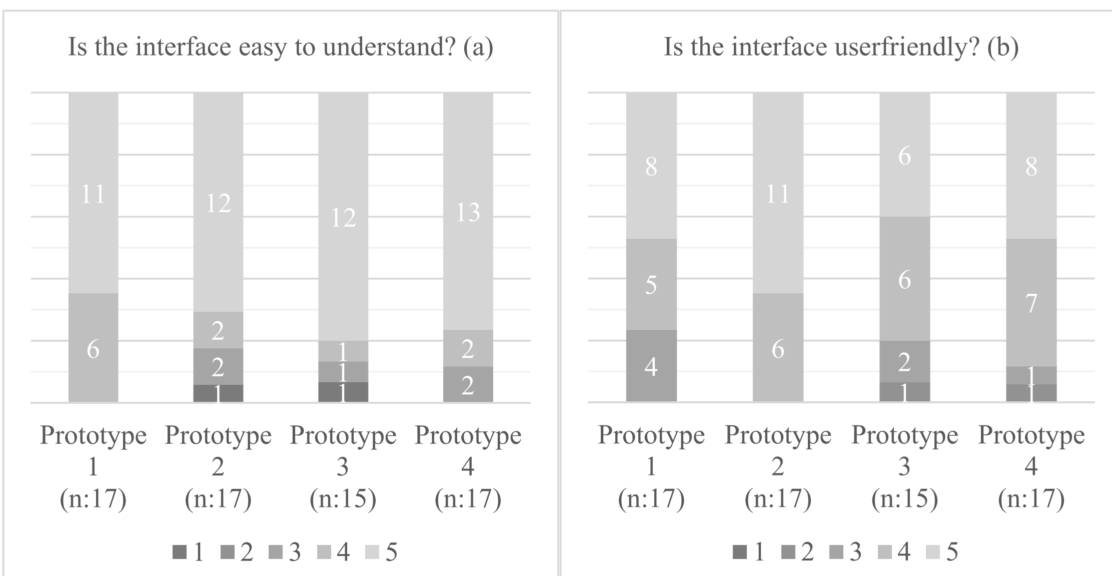



**Figure 4. Overview of the participants' view on the ease of understanding of the prototype interface (a, left) and to what extend they found the concept user friendly (b, right). In both cases 1 is very low and 5 is very high**

We observe that there is only a relatively low variety in how the participants evaluate the ease of understanding the interface of the prototypes (Figure 4a). The user-friendliness of the interfaces (Figure 4b) shows a more mixed evaluation of the prototypes. In terms of mean values, prototype 2 receives the best evaluation followed by prototype 4. The prototypes of higher fidelity, prototypes 3 and 4, are evaluated with larger distribution in the results relative to prototypes 1 and 2.

### 4.3. Desirability

The objective of the final part of the study is to allow the participants to articulate their reflections and experience with the prototypes. By doing so they were encouraged to emphasize which parameters of the prototype they were most fond of and where they could detect room for improvements or changes. Figure 5 summarizes words chosen by the participants from the Product Reaction Cards introduced in the methodology. Figure 6 represents to what extend the participants found the concept attractive, and Figure 7 presents the participants' interests in improving the concept through changes.
When asked to select three reaction cards to describe the prototype, 'Easy to Use' and 'Simplistic' were the most frequent words chosen by the participants. Words like 'Fun', 'User-friendly' and 'Unsafe' became less frequent with the increased level of fidelity. For instance, Participant 5 used the following phrases to describe prototype 2: "It doesn't look secure. The shackle could easily be cut open." This concern of safety was further referred to by three other participants. and participant 31 described prototype 4 using this phrase: "It's very robust", which was mentioned by additional three participants. This indicates that some participants cannot be expected to abstract from what the prototype 'is' and what it is supposed to resemble.


**Figure 5. Word clouds based on the participants' choice of reaction cards to best describe their point of view on the concept; Each cloud represents each of the four prototypes**

Figure 6 presents the results of the study determining to which extent to the participants found the concept attractive. The quantitative results do not articulate any strong variations in how the prototypes were evaluated. The qualitative data, however, gives a more detailed view on the participants' focus and thoughts. A range of examples are how; For prototype 1, participant 1 expressed: "Easy solution to a known problem". For prototype 2, participant 18 expressed "I like the combination pattern, it is fun and innovative." For prototype 3, participant 14 expressed fondness of the size and added "I like the feeling of the joystick". And finally for prototype 4, participant 32 said "It looks like what it is. It is not fancy".

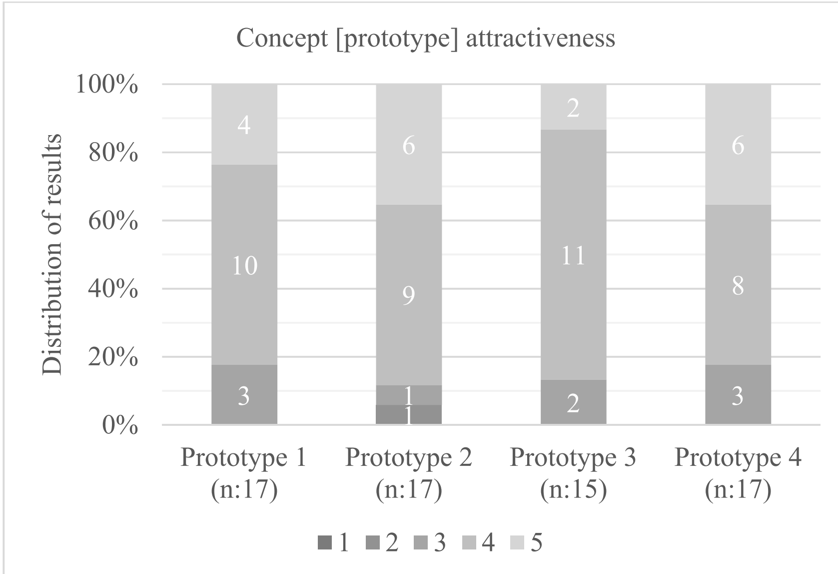



**Figure 6. Evaluation of the extent to which the participants found the concept attractive where 1 is very little and 5 is very much**

Figure 7 presents the participants' interests in performing changes to the padlock concept. As seen in Figure 7 the participants were less interested in suggesting changes to prototypes 1 and 4, whereas they were more interested in changes to the 'mixed-fidelity' prototypes 2 and 3. Concerning prototype 1, Participant 23 claimed: "I don't know what to change based on this cardboard model".

However, some participants did suggest changes to prototype 1. A group of 6 Participants all wanted to change aspects related to the length of the code or the way it was 'put in'. Prototypes 2, 3 and 4 all received inquiries about changing the size of the prototypes (in total n=11). For prototype 2, participant 29 expressed concern of safety: "I don't really know if it will be safe, this [the shackle, red.] is pretty small compared to the rest". For prototype 3, 3 participants addressed size and feeling of joystick. Finally, in prototype 4, 4 participants addressed the looks of the prototype interface; how colors could be better in remembering code or how it would be more appealing to themselves.

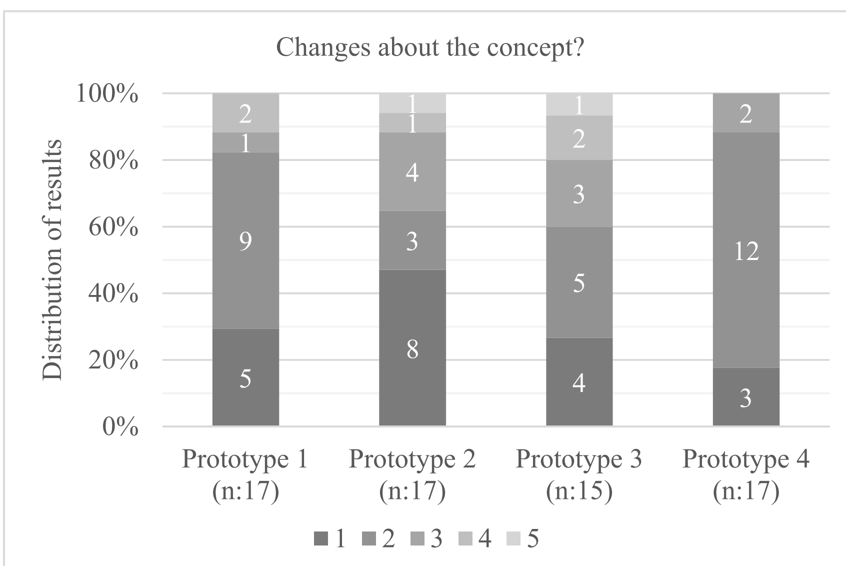



**Figure 7. Evaluation of the participants' interests in improving the concept through changes, where 1 is very little and 5 is very much**

## 5. Discussion

In this section we evaluate the results of the study, and what conclusions can be made in relation to the research questions of the study. Last, we present perspectives on how practitioners can apply these results when establishing prototyping strategies.

### 5.1. Utility

The results document rather large variations in the test-users' ability to interpret the working principle of the mechatronic padlock concept. According to the results, prototypes 1 and 3 are better at communicating the working principle to test-users, whereas an overarching number of test-users misinterpreted prototypes 2 and 4. When evaluating the qualitative data, two characteristics were misinterpreted by the test-users. On prototype 2, the joystick button was (unintentionally) able to rotate, which made a group of 3 participants recognize it as an intended functionality. The authors evaluate that the high fidelity of prototype 4 created unintended noise for determining the working principle. The ergonomic shape, a functional shackle and LED backlights drew attention towards other aspects of the concept rather than functional interface; only for prototype 4 it was suggested by 2 participants that a digital (app or interface) solution was the intended interface for the unlocking mechanism.

For the broader evaluation of how the participants perceived the interface to perform in practice, we observe how the highest mean score was devoted to prototype 2 – this despite the previously highlighted unintended rotating functionality of the joystick. The evaluations do however show a gradual increase in the distribution of evaluations. From the qualitative feedback, we conclude that the increased fidelity helped participants to imagine use cases and associated potential benefits and challenges.

### 5.2. Usability

Only a relatively low variety was recorded in the participants' evaluation of the ease of understanding the interface. For the usability, we observe again an increasing distribution in the results emerging along with the increasing fidelity of the prototypes. In the qualitative feedback, a pattern emerged; participants interacting with prototypes 1 and 2 primarily expressed opinions on the underlying concept and its functionality. These opinions were expressed in combination with questions for clarification in the working principle. Participants interacting with prototypes 3 and 4 articulated their satisfaction with or skepticism on the interaction functionality, how it felt, and other physical attributes like size and color. When collecting qualitative feedback, the interviewers observed how the participants were less likely to interact with prototypes 1 and 2 compared to prototypes 3 and 4 of higher fidelities.

### 5.3. Desirability

The word clouds presented in Figure 5 only show slight variations in terms of occurrences, which indicate a certain degree of commonality in the perception of the prototypes and the padlock concept. The two words 'Fun' and 'Unsafe' occurred less frequently along with increase in prototype fidelity. This underlines the statement that some participants are biased by the particular fidelity represented by the prototype and need a certain level of fidelity to consider the concept a 'safe'.

When evaluating the participants' view on the attractiveness of the concept, all four prototypes were evaluated with only slight variation. Variations in the participants' points of view were to a higher extent articulated when encouraged to provide qualitative feedback. For nine participants the feedback for prototype 1 was related to the underlying the interaction concept for the padlock, while feedback for prototypes 2 six participants articulated the joystick. Feedback for Prototype 3 were in ten cases focused on the joystick and in eight cases its interface. This was so both in terms of the functionality (n=6) and more detailed aspects like the feel of it. Feedback for prototype 4 were similar to that of prototypes 2 and 3, but in a less pronounced way. This trend is further emphasized and mirrored in the participants' interest in improving the concept through changes. We believe that this relates to the fidelity of the prototypes: For prototype 1, the fidelity is so low that it hinders the participants' perception and ability to evaluate the concept. Contrary to this, the fidelity of prototype 4 is very high and the participants are focused on the finish and the details, and are reluctant to provide critique. The 'mixed fidelity' of prototypes 2 and 3 provide a perception of concrete but not finalized design which invites for changes and improvements.

### 5.4. What does this study tell?

With this study, we set out to investigate if the fidelity of prototypes affects users' perception of the concepts that are being tested. We conclude that prototype fidelity does have an influence on how the concept is perceived by test users. However, the results are not linear and without unambiguity. This underlines the previous finding: Prototyping is a complex activity and no one prototype is equally suitable for all design questions (Deininger et al., 2017).

We find that when evaluating how the utility of a concept is perceived, too many functions incorporated in the prototype can introduce noise which may remove focus from the particular aspect of the product design that the designer seeks feedback on. Also unintended functionality of a prototype can result in incorrect interpretations of concept functionality.

In terms of usability, our results suggest that low fidelity prototypes are (resource) effective tools in understanding the needs of test users. Buur and Andreasen have expressed that prototyping is a way of buying information about a future product or service (Buur and Andreasen, 1989). As presented in Table 1 there is a 1:400 cost ratio and a 1:20 ratio in fabrication time between Prototype 1 made of cardboard and Prototype 4 of CNC milled aluminum. When balancing the resources spend with the design insights obtained it is underlined that low fidelity prototypes can be of value and allow for a larger number of design iterations within the same budget constraints.

The findings also indicate that for more concrete evaluations of design solutions, prototypes of higher fidelity can be more suitable. This as participants can more clearly articulate their points of view on particular design aspects that are part of the prototype embodiment. Further, not all stakeholders can be expected to have the level of abstraction necessary to provide rich feedback on a low fidelity prototype.

Based on our findings we recommend practitioners to carefully plan their prototyping activities. Part of this process can include; (i) The design questions will influence what design medium can be utilized for a prototyping activity. When low fidelity prototypes can be used we recommend a large number of low fidelity prototype iterations over few high fidelity iterations. (ii) To conduct fast pre-studies to verify that the exposed prototypes are perceived as intended. (iii) To consider the inclusion of more than one type of prototype to obtain more varied feedback. (iv)To collect a combination of qualitative and quantitative data for varied results.

## 6. Conclusion

This paper presents a study on how the fidelity of prototypes affects the feedback provided by test users. Through 66 semi-structured interviews, participants were presented to one of four different physical prototypes of varying fidelity. The interviews focused on feedback provided by the participants within the three topics: Utility, usability and desirability. Based on the results thereof, we conclude that the fidelity of prototypes affects the feedback from test users – however not in a linear way and not without ambiguity, which underlines the complexity of prototyping activities.

We encourage designers and practitioners to consider the results and recommendations of this and related studies when establishing prototyping strategies. Further, we encourage future research in determining the effect of various design activities on the fidelity of prototypes. This study concerned a concept's desirability to end-users. Further studies could concern how fidelity of prototypes affects assessments of a concepts viability and feasibility by relevant stakeholders.

Several limitations of this study could be addressed in future work; it has only been possible to present a subset of the results from this study in this work. Future work could expand the number of test users and differentiate their demography and cultural backgrounds. Moreover, it could be supported by more in depth analysis and cross evaluation of the results.

### Acknowledgements

The authors would like to thank Martin Meister, Workshop Manager at DTU Skylab, for his support in the fabrication of the prototypes used in this study.

## References


Bailey, B.P. and Konstan, J.A. (2003), "Are informal tools better?: comparing DEMAIS, pencil and paper, and authorware for early multimedia design", *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03), Ft. Lauderdale, USA, April 5-10, 2003*, ACM, New York, pp. 313-320. https://doi.org/10.1145/642611.642666

Barnum, C.M. and Palmer, L.A. (2010), "More than a feeling: understanding the desirability factor in user experience", *CHI'10 Extended Abstracts on Human Factors in Computing Systems (CHI EA '10), Atlanta, USA, April 10-15, 2010,* ACM, New York, pp. 4703-4716. https://doi.org/10.1145/1753846.1754217

Benedek, J. and Miner, T. (2002), "Measuring Desirability: New methods for evaluating desirability in a usability lab setting", *Proceedings of Usability Professionals' Association Conference / the 11th Annual UPA Conference, Orlando, USA, July 8-12, 2002*, pp. 8-12.

Buur, J. and Andreasen, M.M. (1989), "Design models in mechatronic product development", *Design Studies*, Vol. 10 No. 3, pp. 155–162. https://doi.org/10.1016/0142-694x(89)90033-1

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D. et al. (2017), "Design prototyping methods: state of the art in strategies, techniques, and guidelines", *Design Science*, Vol. 3, pp. E13. https://doi.org/10.1017/dsj.2017.10

Camburn, B.A., Dunlap, B.U., Kuhr, R., Viswanathan, V.K., Linsey, J.S. et al. (2013), "Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment", *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 5, Portland, Oregon, USA, August 4-7, 2013,* ASME, pp. V005T06A033. https://doi.org/10.1115/DETC2013-13072

Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K. et al. (2012), "Prototyping Strategies: Literature Review and Identification of Critical Variables", *Proceedings of 2012 ASEE Annual Conference and Exposition, San Antonio, Texas, USA, June 10-13, 2012,* American Society for Engineering Education.

Cooper, R.G. (2001), *Winning at New Products, Accelerating the Process from Idea to Launch*, Basic Books, Perseus Publishing, Cambridge, Massachusetts.

Crilly, N., Moultrie, J. and Clarkson, P.J. (2004), "Seeing things: consumer response to the visual domain in product design", *Design Studies*, Vol. 25 No. 6, pp. 547-577. https://doi.org/10.1016/j.destud.2004.03.001

Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., Obed, S. and Effah Kaufmann, E. (2017), "Does prototype format influence stakeholder design input?", *Proceedings of the 21st International Conference on Engineering Design (ICED '17), Vol 4: Design Methods and Tools, Vancouver, Canada, August 21-25, 2017,* The Design Society, Glasgow, pp. 553-562.

Drezner, J.A. (1992), The Nature and Role of Prototyping in Weapon System Development, RAND, Santa Monica CA, USA.

Gerber, E. (2009), "Prototyping: facing uncertainty through small wins", *Proceedings of the 17th International Conference on Engineering Design (ICED '09), Vol. 9: Human Behavior in Design, Palo Alto, USA, August 24-27, 2009*, pp. 333-342.

Heaton, N. (1992), "What's wrong with the user interface: how rapid prototyping can help", *Proceedings of IEE Colloquium on Software Prototyping and Evolutionary Development, London, UK, November 11, 1992,* IET.

Hostettler, R., Böhmer, A.I., Lindemann, U. and Knoll, A. (2017), "TAF agile framework reducing uncertainty within minimum time and resources", *Proceedings of the 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC), Funchal, Portugal, June 27-29, 2017,* IEEE, pp. 767-775. https://doi.org/10.1109/ICE.2017.8279962

Houde, S. and Hill, C. (1997), "What do prototypes prototype", In: Helander, M.G. Laundauer, T.K. and Prabhu, P.V. (Eds.), *Handbook of Human-Computer Interaction*, 2nd ed., North Holland, pp. 367–381. https://doi.org/10.1016/B978-044481862-1.50082-0

Jensen, L.S., Öense, A.G. and Mortensen, N.H. (2016), "Prototypes in engineering design: Definitions and strategies", *Proceedings of the DESIGN 2016 / 14th International Design Conference, Dubrovnik, Croatia, May 16-19, 2016,* The Design Society, Glasgow, pp. 820-830.

Jensen, M.B., Elverum, C.W. and Steinert, M. (2017), "Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures", *Design Studies*, Vol. 49, pp. 1-31. https://doi.org/10.1016/j.destud.2016.12.002

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", *Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Vol. 7, Cleveland, Ohio, USA, August 6-9, 2017,* ASME, pp. V007T06A033. https://doi.org/10.1115/DETC2017-67173

Lim, Y., Pangam, A., Periyasami, S. and Aneja, S. (2006), "Comparative analysis of high-and low-fidelity prototypes for more valid usability evaluations of mobile devices", *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles (NordiCHI '06), Oslo, Norway, October 14-18, 2006*, ACM, New York, pp. 291–300. https://doi.org/10.1145/1182475.1182506

Menold, J.D. (2017), Prototype for X (PFX): A Prototyping Framework to Support Product Design, PhD thesis, The Pennsylvania State University.

Otto, K.N. and Wood, K.L. (2003), *Product design: techniques in reverse engineering and new product development*, Prentice-Hall.

Reid, T.N., MacDonald, E.F. and Du, P. (2013), "Impact of product design representation on customer judgment", *Journal of Mechanical Design*, Vol. 135 No. 9, pp. 91008. https://doi.org/10.1115/1.4024724

Sauer, J. and Sonderegger, A. (2009), "The influence of prototype fidelity and aesthetics of design in usability tests: Effects on user behaviour, subjective evaluation and emotion", *Applied Ergonomics*, Vol. 40 No. 4, pp. 670–677. https://doi.org/10.1016/j.apergo.2008.06.006

Schrage, M. (2010), "The Culture(s) of PROTOTYPING", *Design Management Review*, Vol. 4 No. 1, pp. 55–65. https://doi.org/10.1111/j.1948-7169.1993.tb00128.x

Sonderegger, A. and Sauer, J. (2010), "The influence of design aesthetics in usability testing: Effects on user performance and perceived usability", *Applied Ergonomics*, Vol. 41 No. 3, pp. 403–410. https://doi.org/10.1016/j.apergo.2009.09.002

Wall, M.B., Ulrich, K.T. and Flowers, W.C. (1992), "Evaluating prototyping technologies for product design", *Research in Engineering Design*, Vol. 3 No. 3, pp. 163–177. https://doi.org/10.1007/BF01580518

Zhang, T., Rau, P.-L.P., Salvendy, G. and Zhou, J. (2012), "Comparing Low and High-Fidelity Prototypes in Mobile Phone Evaluation", *International Journal of Technology Diffusion*, Vol. 3 No. 4, pp. 1-19. https://doi.org/10.4018/jtd.2012100101

Lasse Skovgaard Jensen, PhD student
Technical University of Denmark
Strandboulevarden 141 1 tv., 2100 København Ø, Denmark
Email: lsje@dtu.dk

**Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and information in Engineering Conference**
**IDETC/CIE 2018**
**August 26-29, 2018, Quebec City, Quebec, Canada**

# DETC2018-86293

## PROTOTYPING FOR DESIRABILITY BY DESIGN OF EXPERIMENTS: A CASE STUDY OF A HARDWARE STARTUP

**Lasse Skovgaard Jensen**
PhD Student, Department of Mechanical Engineering, Technical University of Denmark
Kgs. Lyngby, Denmark

**Daniel Vorting**
Co-founder, Alarmified
Copenhagen, Denmark

**Andreas Villadsen**
Co-founder, Alarmified
Copenhagen, Denmark

**Lasse Hylleberg Mølleskov**
Mechanical Design Engineer, Coloplast A/S
Humlebæk, Denmark

**Ali Gürcan Özkil**
Associate Professor, Department of Mechanical Engineering, Technical University of Denmark
Kgs. Lyngby, Denmark

## ABSTRACT
This paper presents a study on how prototyping and 'Design of Experiments' principles can be applied in the early stages of product development. It is explored how four design parameters affect the perceived desirability of a physical alarm device, in development by a small start-up company. By utilizing recent advancements in the tools and platforms, available for the fabrication of prototypes, a range of physical prototypes are made. These prototypes are used to conduct 44 user tests and the results were used to establish a statistical model based on the Response Surface Methodology. The results of the model are outlined, highlighting the primary drivers of product desirability, as well as exemplifying the dynamics among the explored desirability parameters. The statistical model is tested through an experiment, which verifies the model's ability to prescribe the perceived desirability for specific prototypes of the alarm device. The study hereby presents promising results for incorporating Design of Experiment principles in early stages of product development, and the authors encourage further studies to be conducted.

## INTRODUCTION
To fabricate prototypes and perform prototyping activities is an interwoven task for a wide range of product development activities. In recent years, we have witnessed the effects of the Maker Movement and how sub-branches of this paradigm have created a revitalization and renewed focus on both facilities and competencies to support tech-entrepreneurship, as well as the creation of physical prototypes [1]. Within engineering design research, a current research trend focuses particularly on prototyping and how to establish prototyping strategies [2], [3], [4]. Christie et al. define prototyping strategies as "the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)" [4]. Both Camburn et al. and Menold et al. have, as part of their work, proposed different design methodologies to support the creation of prototyping strategies. Definition and fabrication of effective prototypes, while performing best practice prototyping activities, have also been identified as necessary to support a substantial body of prototyping specific knowledge. Lauff et al. have recently documented how such knowledge is currently only being acquired through professional experience, and has underlined this as an underdeveloped competence among e.g. graduate engineering students [5].

Despite the current research focus on prototyping strategies, we argue that successful prototyping strategies cannot be established without a sufficiently comprehensive body of knowledge to support the establishment of such. Within the same context Camburn et al. argue that prototyping is one of the most under-researched topics in engineering design literature [2]. With the aim of expanding the existing body of knowledge on prototyping; the objective of this paper is to explore the application of Design of Experiments (DoE) in prototyping activities, focused on product desirability and early stage product development.

 Copyright © 2018 by ASME

DoE is a quantitative method to conduct experiments which can account for multiple fluctuating parameters. It can be used to assess how significant a change in a single parameter is, as well as the significance of the interaction between multiple parameters. In engineering the principles have historically been most prevalent in the domains of manufacturing and process optimization [6].

The objective was to utilize DoE for providing a systematic and prescriptive approach that supports prototyping for desirability. More specifically this paper presents a case study on systematic prototyping activities. The activities presented were focused on identifying interactions, sensitivity and optimum values for a selection of core design parameters that drive desirability of the product. In particular, this study aims to investigate the following two research questions;

**RQ1:** How can DoE support prototyping in early stage product development, by identifying interactions, sensitivity and optimum values of design parameters driving user desirability?
**RQ2:** What strength and weaknesses can be identified when interlacing prototyping and DoE principles to optimize design parameters for user desirability in early stage product development?

The study was conducted through a case-study of a product development project within a hardware start-up. The development project concerns an anti-theft alarm device that can be attached to different objects. 14 physical low/medium fidelity prototypes of the alarm system were built, where variation was introduced in 4 core design parameters. In total the prototypes represented 37 different product configurations. By utilizing the prototypes, tests with 44 potential users of the product were performed. The tests focused on evaluation of perceived desirability of the product. The specific composition of the prototypes and number of tests to be conducted were established by following a DoE layout. The layout was designed prior to the experiments. In total 3 layouts were designed and learnings were continuously adapted. Lastly, the collected results which in combination describes optimum values and interactions of 4 design parameters, were used to perform a small-scale validation with 7 users.

The contribution of this paper is of exploratory nature and interlaces theory on prototyping, DoE and human centered design. Through the case study it is presented how combining prototyping and DoE principles in early stage product development can generate valuable insights on important design parameters.

## THEORETICAL BACKGROUND

In this section, we build on the work of others and identify opportunities from existing literature on prototyping, consumer value perception and human centered design and DoE.

### Prototypes and prototyping for desirability

A prototype is an artefact that approximates a feature (or multiple features) of a product, service or system [7]. A large body of research documents positive results of using prototypes throughout various design activities [8],[9].
Prototypes are hereby an essential and integrated part of product development and a range of different purposes and characteristics of prototyping is documented to take place throughout the different phases of development projects.

Prototyping is described by Buur and Andreasen as a tool for buying information about a future product [10]. Emerging fabrication tools and platforms which are generally all loosely interconnected around what has become known as The Maker Movement [11],[12] has in the past few years affected what and when it is viable to prototype. This is due to increased availability of at least three types of tools and platforms that can support prototyping activities; The first is digital fabrication technologies - e.g. laser cutters and 3d printers – which have become widely available. They provide new opportunities for fabrication of physical and potentially advanced models [1]. The second is reconfigurable electronics platforms - e.g. the Arduino and Raspberry Pi - and their surrounding environments of digital components, which provide wide opportunities for bringing physical models 'to life' with interactive and digital functionalities [13]. The third is open sharing platforms - e.g. Thingiverse, Github and Instructables – which constitutes a large ecosystem of digital designs, open-source software and guidelines that can support prototyping activities both in terms of inspiration or direct adaption of existing designs [14],[15].

Previous studies have documented how large sunk costs accounting for as much as 50% of development costs historically have been associated with prototyping [16]. New possibilities in prototyping, as e.g. introduced above, can be combined with guided and repeatable approaches for prototyping to support development of more desirable products with faster development processes and potentially also using fewer resources. Here a current research trend underlines the importance of establishing prototyping strategies [4],[13],[17]. One such have been proposed by Menold through the concept "Prototype for X" (PfX) and Prototyping for Desirability, which is seen as the practice of designing prototypes 'that test the purchase-ability of the product' [3]. Despite many positive aspects of this work it can also be argued that the principle lacks the notion of frontloading, where important parameters are determined early in the product development process [18]. Similar to Ulrich and Eppinger's development model [19], prototyping activities follow after concept selection and precedes the final design prior to production. However, as others have argued [20], [21] prototyping is not only a specific phase of product development, but should be considered as an integrated activity along all steps of the development process. In this regard, we see a need for systematic approaches to prototyping in the early stages of product development, which utilizes recent advances in the tools available for prototyping.

 Copyright © 2018 by ASME

### Consumer Value Perception and Human Centered Design

In fields such as retail and marketing, a central topic over decades of research has been *what is valuable to customers*. In 1992, Albrecht argued that "The only thing that matters in the new world of quality is delivering customer value" [22]. Part of delivering value to customers is to understand their preferences. With the objective to describe, explain and predict customer behavior Sheth *et al.* presents a theory consisting of five overall consumption values which are independent of each other. Respectively, Functional Value, Conditional Value, Social Value, Emotional value and Epistemic Value. In total these five values are suggested as a tool to encapsulate an understanding of why consumers make the choices they do [23]. Another attempt to understand value delivered to customers was proposed by Westbrook, who adapted the D-T scale as a tool for measuring customer satisfaction [24]. The scale was originally designed as a tool to measure the quality of life. The use of the D-T scale has been validated through case studies on both products and services where it shows promising results. As a continuation of the work done by Sheth *et al*., Sweenry and Soutar established a 19-item measure scale [25]. The scale is focused on measuring customers' perceived value, with the objective to understand purchase attitude and behavior around consumer goods. The application of the scale has shown promising result when applied in telemarketing.

Understanding customers and what they find valuable also has a long history in the domain of engineering design and product development research. Different benefits and drawbacks from customer involvement in the development process has been a topic of ongoing debate [26],[27]. Product development paradigms such as Design Thinking [28], [29] and the notion of Lead Users by Von Hippel [30] have gained much attention, and has a strong focus on involvement of users or customers in the design process. Positive results of customer involvements are further documented by Salomo *et al*. who argue that customer orientation in innovation projects has a positive influence on new product development success, and that the impact increases with the degree of product innovation [31]. Callahan *et al*. additionally argues that the importance of customer inputs increases with market newness and technological newness of a product [32]. However, others have also identified challenges from involving customers in the product development process. [33]–[35]. Dougherty and Enkel argue that customers may not be able to articulate their needs and desires, and can have unrealistic expectations to the product.

In the retail and marketing domains, it is clear that the customer involvement activities are focused around mature and well-defined products which might already exist in the market. In the product development domain, customers or stakeholders can be involved early in a development process where the product or service is still ill-defined. Here the focus of prototyping activities are often creative and qualitative in nature and take place with reduced requirements or mock-ups as a tool to enable communication with the stakeholders [13], [36]. The value of such activities is well documented but there seems to lack systematic approaches where prototypes are used to generate insights for concrete prioritization and optimization of specific design parameters, despite a low degree of design maturity.

### Design of Experiments

The principles behind DoE was developed by the British statistician Ronald Fisher, in which he described how one could conduct "credible experiments in the presence of many naturally fluctuating conditions such as the soil condition, temperature, and rainfall, in an agricultural experiment" [37]. These principles have later been successfully adapted to other fields like manufacturing and the development of robust products. DoE is used to statistically investigate and evaluate how a change in a parameter contributes to overall performance. This both includes main effects of changing a parameter, but also interaction effects, which are the effects added by a change in multiple parameters [38] [39]. In other words, DoE is a quantitative method to evaluate how significant a change in a single parameter is, and the significance of the interaction between multiple parameters.

A particular characteristic for the existing body of literature, concerning the use of DoE within the domain of engineering, is how it is focused on strictly measurable parameters of physical phenomena, e.g. the robustness of a product design, strength of a welding or the tool-life of a metal cutting process [40]–[44]. Experimental design is an important part of product development and should according to Ellekjær be used in all stages of development [40]. DoE is hereby a recognized approach for understanding how multiple parameters impact response-values and how an optimum for a design parameter can be identified. To the best of knowledge of the authors, no prior examples have been documented, where the DoE principles have been applied to the early phases of product development with the objective to optimize design parameters that drive product desirability and involves user tests.

To summarize; in the previous sections, we have presented literature from three theoretical domains and we identified three opportunities in which this study contributes to the existing body of knowledge;

- A current research trend focuses on prototyping strategies, as well as the use of new technological opportunities for prototyping, but no approach for frontloading through systematic prototyping seems to be available today;
- The existing product development literature combining prototyping and customer involvement in early product development primarily focuses on qualitative evaluation and has less focus on systematic approaches focused on interaction, sensitivity and optimization of design parameters;
- DoE is well known in studies for optimizing physical phenomenon but has not been applied in a prototyping focused end user context, with the objective to optimize subjective design parameters that drive product desirability.


Copyright © 2018 by ASME

The rest of the paper is organized as follows: the following section introduces our methodology and describes how the data was collected and analyzed. Next, we present findings based on analysis of the data corpus. This is followed by a discussion of the results. Finally, we conclude the paper with our reflections and provide directions for future research.

## METHODOLOGY

This case study was conducted as part of a product development project of an anti-theft alarm device. During the early stages of conceptualization, the designers collected quantitative feedback by conducting user tests involving physical prototypes. The objective of the user tests was to understand how the users perceived the desirability of the device when different core design parameters of the prototypes were varied. The user tests were designed and analyzed using a DoE approach and the case study served as a proxy for exploring the use of DoE in this context. The start-up developing the anti-theft alarm device volunteered to conduct the study as part of their development activities.

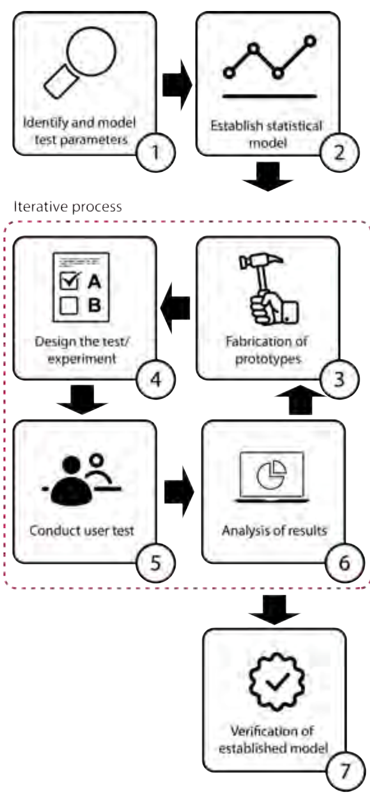



Figure 1. The overall process of the study presented in a 7 step model. Note how the steps 3-6 occur in an iterative manner.

The overall process of the study can be described in 7 steps as presented in Figure 1. The step respectively concerns 1) identification, selection and modelling of relevant test parameters; 2) to establish the statistical model for the study; 3) to fabricate prototypes based on the statistical model; 4) design of the experiments to be conducted; 5) the concrete execution of the user tests and collection of data; 6) analysis of the data to generate results; 7) a verification of the established statistical model.

### Defining Design Parameters

Prior to the study initial brainstorming, conceptualization and functional analysis on the alarm device concept had been conducted by the start-up company. 12 design parameters of potential interest had been identified in this process. To delimit and scope the case study, a focus on 4 design parameters was chosen. The process of narrowing the focus from 12 to 4 design parameters was worked out through a four-step process, as presented in Figure 2.

Figure 2. Design parameter identification process

The first step was a focused literature study. The aim was to clarify whether optimum values for design parameters could be identified in literature. Recommended optimal values were indeed identified for two design parameters. Previous studies of smoke detectors help to clarify optimal design of respectively alarm sound level and the sound pitch/pattern for the alarm device [45], [46]. Due to these findings, the parameters were not included in the user test.

The second step involved identification of links and interactions between design parameters. One recurring design challenge for the start-up's designers was e.g. a trade-off between battery life, component price and size of the battery. The designers hypothesized a small alarm to be attractive, but still needed enough battery life for the device to be desirable. It was decided to investigate the interaction between the parameters Battery Life and Size.

The third step concerned a prioritization of parameters with greatest influence on the desirability of the product. A prioritization was made by utilizing a matrix inspired by the Pugh Method [47] where the start-up's designers drew on their previous experiences. Here, price and size were identified as the parameters with greatest influence on desirability.


Copyright © 2018 by ASME

The fourth step focused on the testability of design parameters. This both in terms of design parameter characteristics – e.g. if they vary as continuous or categorical variables – and how they could be prototyped. Testing intervals for each parameter were defined by studying components datasheets e.g. Li-ion device batteries. Best practice in performing DoE prescribes to include boundaries of the solution space [48], whereas the boundary intervals of the design parameters were defined with values considered as extreme to the designers.

As a result of the four-step process, 4 design parameters were chosen for the study. Respectively the size of the device, the weight, the battery life and the price. The parameters and the intervals within which tests were conducted are presented in Table 1.

Table 1. Design parameters and intervals included in the study. All parameters have characteristics as continuous variables

| Design Parameter | Units | Interval |
|---|---|---|
| Price | DKK | [50-1000] |
| Size | $cm^3$ | [50-500] |
| Battery life | h | [1-1344] |
| Weight | g | [100-400] |

### Study Participants
The start-up had, prior to the study, defined a main customer segment of interest for the case study. The segment was defined as young adults in the age range of 20 – 30 years. An overview of the study participants is presented in Table 2.

Table 2. Overview of study participants

| No. of participants | Age range | Average monthly income | Occupation |
|---|---|---|---|
| 44 | 21-29 | 5500 DKK - 8500 DKK | Students |

### Test Protocol
When conducting the tests, each of the participants were presented with 3 different configurations of the alarm device represented by physical prototypes, as seen in Figure 3. An experiment, whereby multiple variants of a product are presented to the same study participant, is a recognized approach in related studies [49]. The concept of the product was pre-rehearsed and delivered in the same manner for all participants, in order to eliminate variation and potential bias caused by the interviewer. The participants were asked to rate the prototypes individually on a Likert scale of desirability. The participants rating is represented in the results as integers ranging from 1 to 5, where 1 represents the rating 'very undesirable' and 5 represents 'very desirable'. In order to establish a common understanding of the word 'desirable', the participants were presented with the following definition: 'worth having or seeking, as by being useful, advantageous, or pleasing' [50]. If participants asked for further elaboration on design parameters not being tested in the experiment, the response was that the product could always comply. For instance, if a participant was interested in color options for the product, the response would be: *"Whichever color you want it to be"*. This was to eliminate focus on other design parameters, and keep the participants focused on judging the variation of the parameters in question. In other statistical approaches, one would try to keep all out of scope parameters constant, but in this case, doing so was expected to introduce noise [51].

### Prototypes
The prototypes used in the experiments were fabricated by utilizing rapid prototyping tools as introduced in a previous section. In order to keep the main focus of the participants on the varied design-parameters, the prototypes were developed with medium-low fidelity. In total 14 different prototypes were created representing 37 different product configurations when including the communicated price and battery life.

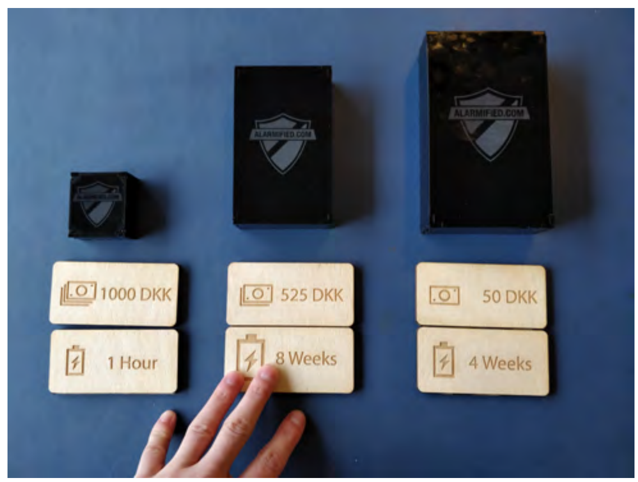


Figure 3. Picture of the prototypes as they were presented to the participants

According to Deininger,[36] the level of fidelity influences how stakeholders perceive the design, and the fidelity of prototypes should be varied based on the desired input from participants. Since form factor was not a parameter of this study, the prototypes were made as simple boxes with finger joints. The battery life and price of the products were presented on signs, while the true weight and size were incorporated in the prototypes. The prototypes had blinking LED's and an engraved logo of the Start-up company. The setup can be seen in Figure 3.

### Experiments
As previously introduced, this study was conducted by applying the principles of DoE. The static modelling in this study is performed by applying the Response Surface Methodology (RSM) originally introduced by Box and Wilson [52]. RMS


Copyright © 2018 by ASME

describes a sequential form of experimentation used to support optimization of a response / outcome through variables made up of a mathematical-statistical model of several input parameters [53]. The basic principle used in this study is that a statistical model is established, where data points collected through user tests are inter- and extrapolated. Hereby an understanding of the different design parameters, their optimums, their sensitivity and the interactions between these can be obtained.

As prescribed by Alexander,[53] an iterative approach can be applied in the process of data collection and data modelling when working with RSM. For this study a total of 3 overall experiments were conducted;

- The first experiment (n=16) was a small pre-study, performed with the objective to evaluate the fit of initial results when modelled with the RSM approach. The pre-study showed promising initial results for the model fit and it was possible to make more informed decision for a larger experiment. Through the pre-study, it was identified that intervals of the design parameters should be expanded in order to explore maximum, minimum, ridge and saddle point regions for the response values.
- The second experiment (n=21) had larger variation across all 4 design parameters. This was done to challenge the initial model.
- Finally, a verification experiment (n=7) was conducted, as it is prescribed by Soravia [39]. The objective was to verify the statistical RSM model by trying to predict the desirability scores of 3 different prototypes.

### Data Analysis

The data modelling and analysis for this study was performed in the software tool SAS JMP. The analysis is based on main effects and interactions of design parameters which proved significant (p-value<0,05). As the experimental results were directly coded on a Likert Scale, it has not been relevant to consider aspects such as interrater reliability values.

## RESULTS

In the following paragraphs we present the results of the study, where DoE principles are applied to study four design parameters influence on the perceived desirability of the alarm device.

### Model Approximation

Figure 4 can be seen as a visualization of the obtained ability to model an approximation of desirability for the alarm device. The figure shows 'Desirability Actual' plotted against 'Desirability Predicted'.

In other words, the plot presents the difference between the actual inputs from the conducted tests and the RSM model predicted by JMP. The $R^2$-value of 0,69 indicates that the model explains 69% of the variability of the response data around its mean. The RMSE (Root Mean Square Error) of 0,7717 indicates the standard deviation of the unexplained variance in the model. The model can hereby predict desirability ratings with a standard deviation of 0,7717.

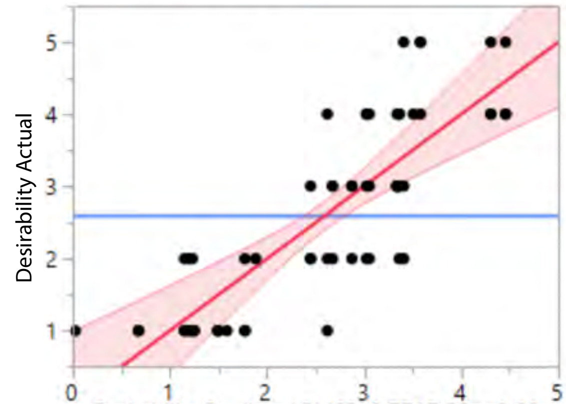



Figure 4.. Plot of actual desirability vs. predicted desirability. Thick bold line indicates model prediction and thin red lines the confidence intervals. Blue line represents mean rated desirability.

The results presented in Table 3 presents the experimental setup in terms of prototype combinations and the results of the second experiment, respectively.

Table 3. Representation of tests conducted in the second experiment. The column to the right represent the average desirability rating of the prototypes.

| Run | Price [DKK] | Size [cm$^3$] | Battery life [h] | Weight [g] | Avg. desirability |
|---|---|---|---|---|---|
| 1 | 1000 | 275 | 1 | 90 | 1,00 |
| 2 | 525 | 275 | 1344 | 188 | 3,33 |
| 3 | 50 | 500 | 1 | 188 | 2,67 |
| 4 | 525 | 275 | 672,5 | 188 | 3,33 |
| 5 | 50 | 500 | 1344 | 188 | 3,33 |
| 6 | 525 | 275 | 672,5 | 90 | 3,00 |
| 7 | 50 | 500 | 672,5 | 90 | 2,33 |
| 8 | 1000 | 50 | 672,5 | 90 | 2,67 |
| 9 | 1000 | 50 | 1344 | 188 | 3,00 |
| 10 | 50 | 50 | 672,5 | 188 | 4,33 |
| 11 | 1000 | 500 | 1 | 90 | 1,33 |
| 12 | 525 | 50 | 1 | 188 | 1,33 |
| 13 | 525 | 50 | 672,5 | 90 | 3,33 |
| 14 | 50 | 50 | 1 | 90 | 1,00 |
| 15 | 50 | 50 | 1344 | 90 | 4,33 |
| 16 | 1000 | 500 | 1344 | 188 | 1,67 |
| 17 | 1000 | 500 | 672,5 | 188 | 1,33 |
| 18 | 525 | 275 | 672,5 | 188 | 3,33 |
| 19 | 50 | 275 | 672,5 | 90 | 4,67 |
| 20 | 525 | 500 | 1 | 90 | 1,00 |
| 21 | 1000 | 275 | 1344 | 90 | 2,33 |


Copyright © 2018 by ASME

## Key Drivers of Desirability

An important aspect of the study was to obtain an understanding of how the included design parameters – and interactions between these parameters along with sensitivity - affects the desirability of the alarm device. Figure 5 presents a graphical illustration of the different parameters influence on desirability.

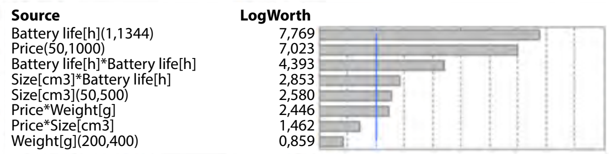



Figure. 5 Graphical illustration of the design parameter(s) influence on desirability of the alarm device. The vertical blue line indicates the significance level of p<0,05. LogWorth is defined as –log(p-value).

The top three drivers of desirability were respectively found to be: battery life, price, and product size in combination with battery life. We are further able to demonstrate that the parameters product size and price in combination with weight has a statistically significant influence on the desirability. Only the parameters price in interaction with size and weight, as an isolated parameter proves to be insignificant in affecting the desirability.

## Dynamics and sensitivity of the Statistical Model

Besides clarifying what drives the desirability of the alarm device, another important aspect of this study is the ability to study the dynamics and sensitivity of the different parameters. As product development often requires different compromises, it is relevant to understand the dynamics and sensitivity of the design parameters in more detail. In this study, these were studied through a prediction profiler tool in SAS JMP.

An example of such dynamics is presented in Figure 6, where the prediction profiler shows that the desirability decreases when the price goes up when other parameters are constant. Also, the Battery Life stagnates at approximately 1000 hours. The interaction of price with weight can also be highlighted. From the profiler, it can be seen that an increase in weight will increase desirability for a product below 250 DKK, but if the price increases above 670 DKK the coefficient of the weights effect becomes negative.

When evaluating the results presented in Figure 7, it is also evident that the model has larger confidence intervals for some combinations of the design parameters - prototype that is small in size but very heavy is one example hereof. Similarly, a large prototype, that is very light follows the same pattern. The size of the confidence intervals in specific areas of the model are related to the number of test runs and related configurations. The more data available the stronger statement strength is obtained for the model.

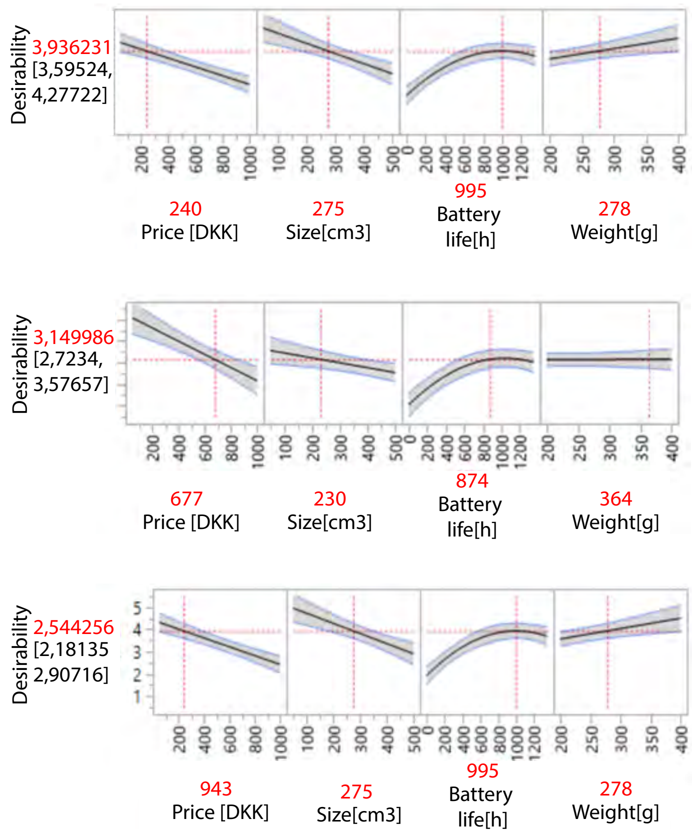



Figure 6. The figures present 3 graphical illustrations of the 4 design parameters and illustrates their dynamics in relation to desirability.

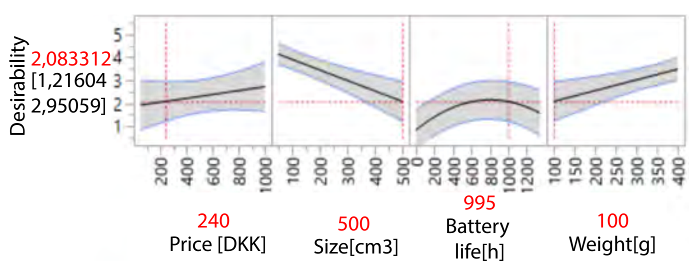



Figure. 7 Prediction profiler with a limited statement strength indicated by large confidence intervals.

It is further worth noticing that some of the combinations of the design parameters can be restricted by certain physical limitations. This is the case for a prototype that is small in size but very heavy. Here, the model approaches the boundaries of what prototypes it was possible to fabricate due to e.g. the natural densities of materials.

## Verification of Statistical Model

As an initial step towards verifying that a DoE approach can be applied for early stage product development a verification of the model was performed.


Copyright © 2018 by ASME

The verification was performed by using the prediction profiler to specify the design characteristics for 3 prototypes. The prototypes were fabricated and user tests (n=7) were conducted following the same experiment-design as previously described. The prototypes specified were, per the statistical model, supposed to be rated 1, 3 and 5 in desirability, when presented to study participants. The results of the verification experiment are presented in Table 4.

Table 4. Results of the verification study. The expected rating by the model is presented in the left column and the average rating form the user test is presented in the column to the right.

| Expected rating | Price [dkk] | Weight [g] | size [$cm^3$] | Battery life [h] | Average rating |
|---|---|---|---|---|---|
| **1** | 600 | 250 | 275 | 2 | **1** |
| **3** | 300 | 300 | 275 | 504 | **2.7** |
| **5** | 150 | 188 | 50 | 1008 | **4.6** |

The results of the verification experiment indicate that the statistical model can be used to predict user desirability ratings. This as the model's prescriptions on expected desirability inline well with the results of the verification experiment. Despite the small sample size, the previously identified RMSE on 0.7717 demonstrates that the average rating of the verification-test is well within the statistical model's error margins. These results support that a DoE approach can be used for user tests to identify design parameters driving desirability. This also provides confidence for the start-up that the results of the study are representative and can be incorporated in the further product development project.

## DISCUSSION

In the following section, we evaluate on the results of the study and the conclusions which can be drawn in relation to the research questions of this study. We will also present recommendations for how the approach could be adapted in related product development activities and what directions future research could focus on.

### DoE in Product Development

Through this case study we have presented how principles of DoE can be applied in early stages of product development. The principles were applied through a 7-step process. Here a statistical model was established by using RSM and in total 3 overall experiments were conducted. The first two experiments and the following verification experiment presents promising results for the approach. The start-up has also obtained insights on how the four design parameters affect desirability of the alarm device.

The start-up company spent a total of 80 hours (40 hours for two developers) on conducting and analyzing the experiments.
The materials and fabrication tools were made available through a local Makerspace.

The authors argue that the product development insights, obtained through this study, were worth the effort, in time and resources. An important enabler is the recent advancements in prototyping tools and platforms utilized for the rapid fabrication of prototypes.

### Opportunities and Limitations

The results of this study are exploratory and do not, despite promising results, allow for any generalization that a similar approach is viable for all development projects. The performance of experiments on topics such as the customer preference of different design variants is already well-established in the food industry[49], [48], [54]. Such distinct, yet related studies support that the DoE principles could have a future role in early stage product development and engineering design methodology focused on product desirability to end users.

An important aspect to consider is the influence of human bias. It can be argued, that the bias embedded in the statistical model to some extent can be representative for the specific target customer group. In the field of social science the human bias of psychological studies often mean that statistical analysis of quantitative responses consider a $R^2$-value of 0.75 as substantial [55].

An obvious pitfall for the approach presented in this study is related to the identification and selection of design parameters. If the driving parameters of core relevance to, for example desirability, are not identified by the designers, it will be an overall limitation to the experiments. Further the designers should have the necessary competences to establish an appropriate statistical model. The authors argue that prior experience, qualitative feedback from early prototyping sessions and the process presented in Figure 2, can be used as support for identifying and selecting relevant design parameters. In terms of statistical modelling the tools available, such as SAS JMP, are constantly improving in terms of usability and support. A large foundational knowledge on statistics might not be a prerequisite for simple modelling activities in the future.

Exceeding what has been presented in this study, there could be wide opportunities in further exploring the dynamics and sensitivity of the design parameters. This could include how to optimize desirability in combination with maximum profitability, for example. It might be that a such 'sweet spot' should be identified by localizing a specific saddle point region in the response values which shows less sensitivity or comply well with the performance of particular standard components, which yield a good tradeoff between costs and product desirability. Here perspectives can be drawn to the Variation Management Framework [56] which theoretically combines


Copyright © 2018 by ASME

Robust Design topics such as the Quality Loss Function, the Transfer Function, and the Domains of Axiomatic Design.

Throughout this study, it has not been in focus to collect qualitative data. Many participants did however express their thoughts and ideas, when they were rating the different prototypes. Future studies could explore the opportunities in collecting and combining such feedback.

## CONCLUSION

This paper presented a study on how prototyping and 'Design of Experiments' principles can be applied in the early stages of product development. It is explored how four selected design parameters affect and drive the perceived desirability of a physical alarm device, which is under development by a start-up company. By building different prototypes, 44 user tests were conducted, and the results were used to establish a statistical model based on the Response Surface Methodology. The results of the model are presented, highlighting the primary drivers of desirability as well as exemplifying the dynamics and sensitivity of the parameters. The statement strength of the statistical model is tested through an experiment, which verifies that the model is able to prescribe a perceived desirability of the product prototypes. The study hereby presents promising results for interlacing prototyping activities and Design of Experiment principles in early stages of product development. We suggest that the approach can help to identify and optimize design parameters that drives product desirability in a frontloading related manner where optimal values are identified early in the development process.
Several limitations and potential improvements of this study could be addressed in future work. Such activities could include use of more advanced statistical modelling, i.e. incorporating dimensions such as the profitability of the final design. We also encourage further research into how qualitative feedback could be incorporated in the study and how different fidelity levels of prototypes or groups of test users might impact the results of the study.

## References

[1] L. S. Jensen, A. G. Özkil, and K. Mougaard, 'Makerspaces in Engineering Education: A Case Study', *Proc. Asme Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, vol. Vol 3, 2016.

[2] B. A. Camburn *et al.*, 'Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment', in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, p. V005T06A033–V005T06A033.

[3] J. Menold, T. W. Simpson, and K. W. Jablokow, 'The Prototype for X (PFX) Framework: Assessing the Impact of PFX on Desirability, Feasibility, and Viability of End Designs', 2016, p. V007T06A040.

[4] E. J. Christie *et al.*, 'Prototyping Strategies: Literature Review and Identification of Critical Variables', in *American Society for Engineering Education*, 2012.

[5] C. Lauff, D. Kotys-Schwartz, and M. E. Rentschler, 'Perceptions of Prototypes: Pilot Study Comparing Students and Professionals', 2017, p. V003T04A011.

[6] L. Eriksson, E. Johansson, N. Kettaneh-Wold, C. Wikström, and S. Wold, 'Design of experiments', *Princ. Appl. Learn Ways AB Stockh.*, 2000.

[7] K. N. Otto and K. L. Wood, *Product Design: Techniques in Reverse Engineering and New Product Design*. Prentice-Hall., 2001.

[8] M. B. Wall, 'Making sense of prototyping technologies for product design', Massachusetts Institute of Technology, 1991.

[9] M. Schrage, 'The Culture(s) of PROTOTYPING', *Des. Manag. J. Former Ser.*, vol. 4, no. 1, pp. 55–65, 2010.

[10] J. Buur, 'Design models in mechatronic product development', *Des. Stud.*, vol. 10, no. 10, pp. 155–162, 1989.

[11] C. Anderson, *Makers: The New Industrial Revolution*. Random House LLC, 2012.

[12] H. Lipson and M. Kurman, *Fabricated: The new world of 3D printing*. John Wiley & Sons, 2013.

[13] B. Camburn *et al.*, 'Design prototyping methods: state of the art in strategies, techniques, and guidelines', *Des. Sci.*, vol. 3, p. e13, Aug. 2017.

[14] A. G. Özkil, 'Collective design in 3D printing: A large scale empirical study of designs, designers and evolution', *Des. Stud.*, vol. 51, pp. 66–89, Jul. 2017.

[15] B. A. Camburn *et al.*, 'The Way Makers Prototype : Principles of DIY Design', *Proc. ASME 2015 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, vol. 7, pp. 1–10, 2015.

[16] R. G. Cooper, 'Winning at New Products, Accelerating the Process from Idea to Launch, 2001', *Camb. Perseus*, 2001.

[17] B. U. Dunlap *et al.*, 'Heuristics-based prototyping strategy formation: development and testing of a new prototyping planning tool', in *ASME 2014 International Mechanical Engineering Congress and Exposition*, 2014, p. V011T14A019–V011T14A019.

[18] S. Thomke and T. Fujimoto, 'Effect of `front-loading' problem-solving on product development performance', *J. Prod. Innov. Manag.*, vol. 17, no. 2, pp. 128–142, Mar. 2000.

[19] Ulrich and Eppinger, *Product design and development*. McGraw-Hill Higher Education, 2007.

[20] C. Lauff, D. Kotys-Schwartz, and M. E. Rentschler, 'What is a Prototype?: Emergent Roles of Prototypes From Empirical Work in Three Diverse Companies', 2017, p. V007T06A033.

[21] M. B. Jensen, C. W. Elverum, and M. Steinert, 'Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures', *Des. Stud.*, vol. 49, pp. 1–31, Mar. 2017.

[22] B. J. Babin, W. R. Darden, and M. Griffin, 'Work and/or fun: measuring hedonic and utilitarian shopping value', *J. Consum. Res.*, vol. 20, no. 4, pp. 644–656, 1994.

 Copyright © 2018 by ASME

[23] J. N. Sheth, B. I. Newman, and B. L. Gross, ‘Why we buy what we buy: A theory of consumption values’, *J. Bus. Res.*, vol. 22, no. 2, pp. 159–170, 1991.

[24] R. A. Westbrook, ‘A rating scale for measuring product/service satisfaction’, *J. Mark.*, pp. 68–72, 1980.

[25] J. C. Sweeney and G. N. Soutar, ‘Consumer perceived value: The development of a multiple item scale’, *J. Retail.*, vol. 77, no. 2, pp. 203–220, 2001.

[26] G. Groenewegen and F. de Langen, ‘Critical Success Factors of the Survival of Start-Ups with a Radical Innovation’, *J. Appl. Econ. Bus. Res.*, vol. 2, no. 3, pp. 155–171, 2012.

[27] L. Scaringella, ‘Involvement of “Ostensible Customers” in really new innovation: Failure of a start-up’, *J. Eng. Technol. Manag. - JET-M*, vol. 43, pp. 1–18, Jan. 2017.

[28] T. Kelley and J. Littman, *The art of innovation : lessons in creativity from IDEO, America’s leading design firm*. Currency/Doubleday, 2001.

[29] H. W. Chesbrough, ‘Open Innovation: The New Imperative for Creating and Profiting from Technology.’, *Havard Bus. Press*, 2003.

[30] E. Von Hippel, ‘Democratizing innovation: the evolving phenomenon of user innovation’, *Int. J. Innov. Sci.*, vol. 1, no. 1, pp. 29–40, 2009.

[31] S. Salomo, F. Steinhoff, and V. Trommsdorff, ‘Customer orientation in innovation projects and new product development success - the moderating effect of product innovativeness’, *Int. J. Technol. Manag.*, vol. 26, no. 5–6, pp. 442–463, 2003.

[32] J. Callahan and E. Lasry, ‘The importance of customer input in the development of very new products’, *RD Manag.*, vol. 34, no. 2, pp. 107–120, Mar. 2004.

[33] D. Dougherty, ‘Reimagining the Differentiation and Integration of Work for Sustained Product Innovation’, *Organ. Sci.*, vol. 12, no. 5, pp. 612–631, Oct. 2001.

[34] E. Enkel, J. Perez-Freije, and O. Gassmann, ‘Minimizing Market Risks Through Customer Integration in New Product Development: Learning from Bad Practice’, *Creat. Innov. Manag.*, vol. 14, no. 4, pp. 425–437, Dec. 2005.

[35] E. Enkel, C. Kausch, and O. Gassmann, ‘Managing the risk of customer integration’, *Eur. Manag. J.*, vol. 23, no. 2, pp. 203–213, Apr. 2005.

[36] M. Deininger, S. Daly, K. Sienko, J. Lee, S. Obed, and E. Effah Kaufmann, ‘Does Prototype Format Influence Stakeholder Design Input?’, *Proc. 21st Int. Conf. Eng. Des. ICED17*, vol. 4, no. August, pp. 553–562, 2017.

[37] K. M. Ramachandran and C. P. Tsokos, ‘Design of Experiments’, in *Mathematical Statistics with Applications in R*, Elsevier, 2015, pp. 459–494.

[38] R. J. Vechio, *Understanding Design of Experiments*. Hanser Publishers, 1997.

[39] S. Sergio and A. Orth, *Design of Experiments*. Wiley, 2012.

[40] M. Risberg Ellekjær and S. Bisgaard, ‘The use of experimental design in the development of new products’, *Int. J. Qual. Sci.*, vol. 3, no. 3, pp. 254–274, Sep. 1998.

[41] H. Rowlands and J. Antony, ‘Application of design of experiments to a spot welding process’, *Assem. Autom.*, vol. 23, no. 3, pp. 273–279, 2003.

[42] V. P. Astakhov, ‘Screening (Sieve) Design of Experiments in Metal Cutting’, Springer, Cham, 2016, pp. 1–37.

[43] M. Dittrich, M. Dix, M. Kuhl, B. Palumbo, and F. Tagliaferri, ‘Process Analysis of Water Abrasive Fine Jet Structuring of Ceramic Surfaces via Design of Experiment’, *Procedia CIRP*, vol. 14, pp. 442–447, 2014.

[44] N. Khanna, ‘Design of Experiments in Titanium Metal Cutting Research.’, *Des. Exp. Prod. Eng.*, pp. 165–182, 2016.

[45] D. Bruck and M. Ball, ‘Optimizing Emergency Awakening to Audible Smoke Alarms: An Update’, *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 49, no. 4, pp. 585–601, Aug. 2007.

[46] R. W. Huey, D. S. Buckley, and N. D. Lerner, ‘Audible performance of smoke alarm sounds’, *Int. J. Ind. Ergon.*, vol. 18, no. 1, pp. 61–69, Jul. 1996.

[47] S. Pugh and D. Clausing, *Creating innovtive products using total design: the living legacy of Stuart Pugh*. Addison-Wesley Longman Publishing Co., Inc., 1996.

[48] R. F. Gunst, *Response surface methodology: process and product optimization using designed experiments*. Taylor & Francis Group, 1996.

[49] O. Acosta, F. Víquez, and E. Cubero, ‘Optimisation of low calorie mixed fruit jelly by response surface methodology’, *Food Qual. Prefer.*, vol. 19, no. 1, pp. 79–85, Jan. 2008.

[50] J. Benedek and T. Miner, ‘Measuring Desirability: New Methods for Evaluating Desirability in a Usability Lab Setting’, *Proc UPA 2002*, p. 5, 2002.

[51] Thequalityportal.com, ‘Robustness P-Diagram :: Overview’, 2007. [Online]. Available: http://thequalityportal.com/p_diagram.htm. [Accessed: 06-Mar-2018].

[52] G. E. Box and K. B. Wilson, ‘On the experimental attainment of optimum conditions’, in *Breakthroughs in statistics*, Springer, 1992, pp. 270–310.

[53] M. T. Alexander, *Response surface optimization using JMP® software*. 2000.

[54] D. Baş and İ. H. Boyacı, ‘Modeling and optimization I: Usability of response surface methodology’, *J. Food Eng.*, vol. 78, no. 3, pp. 836–845, Feb. 2007.

[55] J. F. Hair, C. M. Ringle, and M. Sarstedt, ‘PLS-SEM: Indeed a silver bullet’, *J. Mark. Theory Pract.*, vol. 19, no. 2, pp. 139–152, 2011.

[56] T. J. Howard, T. Eifler, S. N. Pedersen, S. M. Göhler, S. M. Boorla, and M. E. Christensen, ‘The variation management framework (VMF): A unifying graphical representation of robust design’, *Qual. Eng.*, vol. 29, no. 4, pp. 563–572, Oct. 2017.


 Copyright © 2018 by ASME

# Fostering prototyping mindsets: Towards the framework 'Prototyping Planner'

*Jensen, Lasse Skovgaard; Özkil, Ali Gürcan*
*Department of Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark*

## Abstract
This paper introduces the prototyping framework 'Prototyping Planner' which is evaluated through a controlled experiment with participation of 20 teams of novice designers. The aim is to evaluate the internal and external validity of the framework. The study is based on survey data focused at the perceived effect of the tool and interrater evaluation of the design teams build logs, where it is investigated to what extend a set of best practice prototyping principles are being practiced. Our analysis reveals that i) the layout of the support tool is evaluated to be attractive and ii) helped the participants in developing a 'prototyping mindset'. Further, it is revealed that iii) the use of 'Prototyping Planner' lead to significant improvements in the design team's application of prototyping best practice principles. The authors also identify discrepancies between the survey data and the best practice prototyping evaluations. These insights are discussed and suggested as probes for further refinement of the framework. The results of this study provides empirical insights on the dynamics of a prototyping framework, which can be of interest to both practitioners and researchers.

## 1 Introduction
In todays globalized markets products, services and their associated business models are becoming ever more complex. Such complexity also feeds back into the product development process, where todays designers are required to understand a wider context in addition to the technical design process. One of the tools available for designers to obtain such understanding is to use prototypes to 'buy' such kind of insights throughout the product development process.
In the topic of prototyping, the recent years have witnessed a vast development and availability in digital desktop fabrication tools for prototyping (Jensen et al., 2016). The new tools, such as 3d printers and laser cutters, are introducing new opportunities, but are also creating a more omniscient roles of designers (Wall et al., 1992).

In combination this increasing complexity of product development and new tools has helped spark a growing interest in research focused at prototyping and prototyping frameworks (Menold et al., 2017), (Camburn et al., 2017) to support designers in their prototyping activities. Despite this growing interest in prototyping, there is a current lack of assessments and evaluations of prototyping frameworks. In particular, little is known about how designers perceive their value and their ability to elevate best practice principles in prototyping throughout the development process.

In engineering design literature, the design efforts of respectively design experts and novice designers have often been studied. In this study we present how there is a current need for supporting novice designers in their prototyping activities. It is underlined that development of competencies for prototyping require an understanding that incorporates contextual dimensions that e.g. includes the planning-, fabrication-, exposure- and learnings of prototyping.

We base our study on the introduction of a process focused prototyping framework named 'Prototyping Planner' and this work hereby sought to answer the following research questions;

- RQ1: How does the introduction of a prototyping framework affect the perceived product development process of design teams?

- RQ2: How does the introduction of a prototyping framework affect the extend of best practice prototyping principles being performed by design teams?

'Prototyping Planner' was conceptualized, drawing inspiration from existing research and feedback from expert practitioners in industry. The framework is evaluated in a design challenge conducted as a controlled experiment with participation of 20 teams of novice designers (129 participants in total). The design challenge was conducted in collaboration with Bang & Olufsen. It concerns fabrication of wireless HIFI speakers and utilizes digital fabrication and collective design platforms. The analysis outlined in the study was based on survey data and interrater evaluation of the design teams build logs.

It is the objective that the introduction – and further development – of 'Prototyping Planner' can support novice designers, and small development teams in hardware start-ups, by improving their prototyping activities, essentially leading to increased chances of successful products.

The rest of the paper is organized as follows; The following section introduces theoretical aspects and state of the art in research on prototyping. Next, we present our methodology which includes i) an introduction to the conceptualization of 'Prototyping Planner' and ii) describes how the data is collected and handled. The fourth section presents our findings based on our analysis of the data corpus, which is then followed by a discussion of the results. Finally, we conclude the paper with our reflections and provide directions for future research.

# 2 Theoretical Background

In this section we introduce theoretical aspects of prototyping and also compile a body of literature to illustrate how different studies have identified shortcomings of prototyping efforts of novice designers.

## 2.1 Prototypes in engineering design and product development

To fabricate prototypes and perform prototyping activities is an interwoven task for a wide range of product development and design activities. Prototypes can help to create, explore, describe, test and analyze the item being designed. For this study we adopt the definition of a prototype from Otto and Wood: "A prototype is an artefact that approximates a feature (or multiple features) of a product, service or system" (Otto and Wood, 2003).

### 2.1.1 Emerging tools for prototyping

Along with changes in our products and services, the role and the importance of prototyping is also changing. Emerging software platforms (Özkil, 2017), new digital fabrication technologies (Jensen et al., 2016), and reconfigurable electronics platforms (Camburn et al., 2017) provides new opportunities in how prototyping can be conducted. This as the aforementioned development has enabled a drastic cost reduction in single unit manufacturing for prototyping (Camburn et al., 2017).

In other words; the costs, time allocation and 'barrier of entry' for prototyping in product development is lowering. Wall et al. made an early observation regarding such desktop prototyping technologies, and argued that consequently the knowledge and skills of fabricators are diminished and centralized decision-making around the designer (Wall et al., 1992). Various prototyping decisions are hereby centralized around the designer. This new development calls for the design community to study prototyping activates and incorporate these new opportunities in support.

## 2.2 Prototyping strategies and frameworks

The above introduced development has helped spark a renewed interest in prototyping, and within engineering design research, a current research trend focuses particularly on prototyping and how to establish prototyping strategies and prototyping frameworks. Christie et al. define prototyping strategies as "the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)" (Christie et al., 2012). In a recent study by Menold et al. the authors identified six existing support tools or guidelines (Menold et al., 2018) to help designers in prototype fabrication. Examples are; Christie et al. who suggested thirteen decision variables to consider in establishment of a prototyping strategy, along with nine factors characterizing decisions regarding the design approach. This e.g. that the approach to prototyping can consist of multiple concepts in parallel vs. prototyping only a single concept. The focus of the work is respectively on the functionality of the prototype and on optimal management of resources allocated to prototyping activities (Christie et al., 2012). Camburn et al. have suggested a hierarchical list of decisions for a broad prototyping strategy. The method consists of the four primary phases; i) Determination of the number of iterations required, ii) Evaluation of the need for scaling, functional isolation, and subsystem isolation, iii) Determination of which concepts to pursue in parallel, iv) To write-up prototyping strategy (Camburn et al., 2013).

A shared characteristic for the six identified prototyping support tool, are their main focus at respectively i) Optimization of resource allocation of the time and cost associated with prototype fabrication, and ii) Performance assessment of the final design outcomes. A similar argument has been presented by Menold et al., who argue that existing prototyping frameworks have mainly assessed a single attribute, e.g. the feasibility of the final designs, or optimization of resource use during the prototyping process (Menold et al., 2018). This also underlines a lacking assessments and evaluations of prototyping frameworks. In particular, little is known about their perceived value and ability to elevate best practice principles in prototyping, being performed by the design team.

With offset in the identification of this limited focus of existing prototyping support, Menold et al. have proposed the 'prototype for X' framework which incorporated human centered design aspects, such as user satisfaction and user-perceived value  (Menold et al., 2016).

While there is a place for all of the existing prototyping support, we argue that there is still an existing need for prototyping support that encompasses prototyping holistically as a process and not primarily as a fabrication activity. Prototyping is an interwoven and often complex product development activity. It requires an overall project understanding to define, plan, execute and evaluate prototyping activities. In the next section we underline this need by highlighting how novice designers are often challenged in their prototyping activities.

## 2.3 Novice designers in product development and prototyping

In the design community it is generally recognized that the design performance of novices and experts differ. Hereby support tools are of high value to guide designers with limited or intermediate experience in particular topics. In that perspective a range of studies have been focused at understanding differences in the behavior of experienced and novice designers (Smith and Leong, 1998), (Ozkan and Dogan, 2013) (Ahmed et al., 2003), (Ahmed and Wallace, 2004) (Atman et al., 2007). These studies share the overall finding that experienced designers were superior in employing design strategies, and one of the objectives for understanding difference in behavior is to identify what aspects of the design activity to support. By reviewing the existing literature, we highlight three general product development competencies which are identified as underdeveloped among novice designers, and additionally five that are specific to prototyping. These are presented in Table 1 below.

*Table 1: Development competencies of novice designers vs. expert designers*

| Design aspect | Novice designer | Expert designer | Reference |
|---|---|---|---|
| *General product development competencies* | | | |
| **Problem scoping** | Spend less time in problem scoping and information gathering. | Spend more time in problem scoping and information gathering. | (Atman et al., 2007) |
| **Design decisions** | Trial and error with immediate implementation, omitting preliminary evaluation. | Makes preliminary evaluations of their design decisions prior to implementation. | (Ahmed et al., 2003) |
| **Design performance in non-routine situations** | If support is available performance is comparable to expert. | "Benchmark performance" | (Daalhuizen and Badke-Schaub, 2011) |
| *Competencies of particular relevance to prototyping* | | | |
| **Role of prototypes** | Physical models created in the later phases of development process with the objective to evaluate a chosen design. | Dynamic tools of various forms to help refine or explore ideas throughout the whole development process. | (Lauff et al., 2017) (Deininger et al., 2017) |
| **Awareness** | Not always aware of own broad range of prototype usage. | Prototypes used to aid in making decisions, and a tool to learn about unknowns. | (Deininger et al., 2017) (Lauff et al., 2017) |
| **Prototyping approach** | Lack specificity in prototyping practice. | N/a | (Deininger et al., 2017) |
| **Sub-system isolation and reduction of uncertainty** | Incrementally approaching envisioned product rather than partial designs and uncertainty reduction. | Prototype only parts of the system and systematically prototype the minimum model needed. | (Viswanathan et al., 2014) (Hostettler et al., 2017) |
| **Fixation from prototyping** | Lacking building and testing skills can lead to design fixation. | Proficient building and testing skills reduce fixation from sunk cost. | (Viswanathan et al., 2014) |

As outlined in Table 1 novice designers are reported to have a limited understanding of prototypes and prototyping activities (Lauff et al., 2017). Comparatively, professionals showed a broader perception and utilization of prototypes as an aid in making decisions, and a tool to learn about unknowns throughout the design process. Hostettler et al. have underlined that novice designers working on 'agile hardware' projects, despite very frequent prototyping simply lacked the ability to concretize the purpose of prototyping (Hostettler et al., 2017). This ability to define and fabricate effective prototypes seem to require a substantial body of prototyping specific knowledge (Lauff et al., 2017). Despite the challenges presented in Table 1, there currently seems to be no prototyping tools available to holistically support prototyping efforts of novice designers.
Prototyping support is hereby of obvious relevance, which is further underlined by a recent study, showing that professors engaged in engineering education evaluate prototyping skills as a central competence to engineers, but are significantly less proficient in delivering education which incorporates prototyping activities (Jensen et al., 2016).

### 2.4 Research objectives

To summarize, in the previous sections, we have presented literature from theoretical domains underlining that prototyping is an interwoven and often complex product development activity. In this process we have identified literature gabs in which this study contributes to expand the existing body of knowledge. Below we list three concrete aspects hereof:

- Emerging tools for prototyping are introducing new opportunities, but also more omniscient roles of designers, which needs to be studies and supported.
- Currently there is a lack of assessments and evaluations of prototyping frameworks. In particular, little is known about their perceived value and ability to elevate best practice principles in prototyping being performed by design teams.
- Finally, a range of literature underline how prototyping practices of novice designers could be improved. Concretely this study proposes a prototyping framework.

In the next section we introduce our research methods and also how the prototyping framework 'Prototyping Planner' was conceptualized.

## 3 Research methods and conceptualization of 'Prototyping Planner'

This part of our paper serves two purposes and is presented in two overall sections. This first, is an introduction to the conceptualization of 'Prototyping Planner', which also summarizes empirical insights obtained through a workshop with practitioners. The second, outlines the controlled experiment and describes how the data is collected and handled.

### 3.1 Conceptualizing 'Prototyping Planner'

'Prototyping Planner' is dedicated novices with limited or intermediate product development experience. It is the ambition to provide a prototyping framework that supports prototyping as a contextual activity. To do so, the authors evaluated the findings presented in Table 1, which illustrates areas of lacking competencies among novice designers. Part conclusions are that the framework should encourage use of prototypes for a wide range of purposes, but also underline that designers should be specific in defining prototyping objectives. Further it should encourage sub-system isolation, preliminary evaluations and exploration of design aspects with high uncertainty rather than incrementally prototyping towards the final product. With offset in these insights and further studies of existing literature on prototyping, an initial layout of 'Prototyping Planner' was proposed.

'Prototyping Planner' follows an overall four step process as a reinterpretation of the Shewhart Cycle described by Deming (Deming, 1986). The cycle is here represented in the four steps: Think, Build, Expose and Act.
The Shewhart Cycle has also served as inspiration for the TAF Agile Framework that has emerged from hackathons organized at TU Munich in Germany (Hostettler et al., 2017). Where TAF is focused at maneuvering agile product development projects, 'Prototyping Planner' is focused on providing support for the concrete prototyping activities and are intended for dynamic integration in development activities independent of the overall development methodology.

### 3.1.1 Feedback from industry practitioners

In order to collect feedback on an initial outline of 'Prototyping Planner', industry practitioners were invited for a four-hour workshop. Eight potential participants were identified through a Linked-In search focused on previous professional prototyping experience and proximity to the Technical University. Five practitioners volunteered to participate and represented experiences in product development responsibility in a tech start-up, medical device R&D and product development consultancy. A photo from the workshop is shown in Figure 1 below.


*Figure 1: Workshop participants taking personal notes during prototyping exercise to evaluate early version of 'Prototyping Planner'*

The workshop covered five main topics i) A general introduction to 'Prototyping Planner' and the objectives of the support. ii) A 30 min individual prototyping exercise focused at applying 'Prototyping Planner' in a recent prototyping activity of the participants. iii) Personal brainstorming and documentation on prototyping best practice experiences. iv) Individual presentation of results and common discussion on what characterizes best practice. v) Collaborative exercise in reducing dimensionality of 16 individual suggestions into five recommendations for 'Prototyping Planner'.

Feedback from the workshop was generally positive regarding the overall concept of 'Prototyping Planner'. It was e.g. supported that effective prototyping should balance both the prototype specification, fabrication and the prototyping activity (e.g. testing, exploration etc.) in order to establish a coherent prototyping strategy.

The workshop supported the authors in refining the tool e.g. participants suggested flexibility in applying varying level of detail, dependent on the level of support desired by the user – similar suggestions have also been proposed by (Daalhuizen and Badke-Schaub, 2011)

The five concrete recommendations, which have been sought implemented are the following:

i. Identify clear purpose of prototypes, especially under convergent development contexts.
ii. Fabricate only the minimum model needed to obtain sufficiently accurate results.
iii. Perform preliminary evaluations to ensure appropriate prototype resolution and fidelity.
iv. Allow experimentation and exploration to identify unknowns and refine understanding, when uncertainty is high.
v. Encourage use of prototypes for communication and knowledge sharing purposes among team members.

#### 3.1.2 Layout of 'Prototyping Planner'

As introduced above 'Prototyping Planner' consists of the four overall steps: Think, Build, Expose, Act. The layout of 'Prototyping Planner' can be assed in more detail in appendix 1.

All four steps are iteratively visited as a clarification activity prior to engaging in prototype fabrication and prototyping exposure. Each of the four steps include domain related questions to cultivate reflections, guiding the design team to adapt best practice behavior. Finally, preceding the four step process the design team is encouraged to establish respectively a Build Plan, an Expose Plan and an Act Plan for the prototyping activity. The four steps are the following;

Think; The focus of the think step is to reflect on the development project and clarify the current objectives, e.g. if the current objectives require a divergent or convergent development approach (Cross, 2008). Further the 'determine characteristics' are closely coupled to questions regarding the prototype fidelity and resolution required for the particular situation (Schmidt et al., 2017), (Jensen et al., 2018a). Finally, it is to be determined what lens and domain to focus the activity on. Here referring to respectively desirability, viability and feasibility aspects of the product (Kelley and Littman, 2001) which often are determinants for prototype characteristics e.g. 'proof of concept', 'Looks like', 'Works like' or 'Manufacturing' prototypes (Einstein, 2015a).

Build; The focus of the Build step, is to prepare the prototype fabrication by taking into account the most optimal prototype scope – e.g. if a subsystem can be isolated (Camburn, 2015) or if commercial products can be utilized by hacking or reverse engineering (Camburn and Wood, 2018). Further reflections concern the concrete prototype fabrication; What is the minimum model needed? And should it be fabricated in-house or outsourced? (Wall et al., 1992), what documentation is required, if the same or different materials, manufacturing and assembly techniques than for the final design are favorable (Christie et al., 2012). The last headline suggests considerations regarding time and budgets required, and finally the generated information all feed into establishing the build plan.

Expose; The expose step focuses on defining the activity, where the prototype is put into use, either by exploring its capabilities or performing a specific test, related to as a falsifiable hypothesis or design question being investigated. The test headline reflects practical aspects, such as; How many times should the test be conducted? How long will it take? What stakeholders, equipment or other requirements will the test include? (Ulrich and Eppinger, 2007) The collect headline is focused on how generated data should be characterized and collected. Finally, the generated information all feed into establishing the expose plan.

Act; The Act step is focused on evaluating the obtained insights. The learnings headline encourages to summarize learnings and potential unexpected outcomes in relation to hypothesis' or design questions. The adaptions headline is focused at clarifying what actions and next steps can be derived from the results? Dissemination has been entitled a headline of its own to encourage knowledge sharing actions. As the last step of 'Prototyping Planner', the Act Plan lists information that influences how to continue the project.

## 3.2 Research design and methods

The study outlined in this paper was conducted as a controlled experiment at a Technical University in Scandinavia. 129 novice designers - engineering students - participated in the study, as part of a hands-on project based course hosted at a university Makerspace. The experiments evaluates the design activities of projects focused on the design, development and fabrication of fully functional wireless HiFi loudspeakers. Figure 2 below presents the results of the experiment conducted in 2017. In the following sections it is outlined how the study was conducted.


*Figure 2 Presentation of the 10 speakers designed, developed and fabricated during the 2017 experiment.*

### 3.2.1 Participants and design teams

All participants were enrolled in the Design Engineering program offered by the Technical University, and besides their competencies within fundamental engineering topics, the participants all had experience from at least 20 ETCS credits of project based courses, focused on product development. This including engagement with stakeholders, prototyping and use of engineering design methodology to support design and collaboration. Descriptive characteristics for the participants are presented in Table 2 below.

*Table 2: Descriptive characteristics of the participants*

| **Year** | **2016** | | **2017** | | **2018** | |
|---|---|---|---|---|---|---|
| Number of participants | 66 | | 64 | | 65 | |
| Design Teams | 10 team | | 10 | | 10 | |
| Age distribution | 21 – 33 years | | 20 – 29 years | | 20 – 28 years | |
| Gender | Females | Males | Females | Males | Females | Males |
| | 28 | 38 | 25 | 39 | 24 | 41 |

The participants were allowed to form their own design teams at the beginning of the project. Such approach was considered important when staging an entrepreneurial environment, where shared points of view and community is part of what start-up founders and employees favor in their 'corporate culture.'

### 3.2.2 Experimental procedure

The design challenge for this experiment concern the design, development and fabrication of fully functional wireless HiFi loudspeakers, which were brought to life over a 7-week timespan. The experiment was repeated three times over the period 2016 – 2018, as outlined in Figure 3 below.
The first experiment was conducted as a pre-study to clarify how the design teams performed, and if the design challenge was well scoped and suitable for this experiment. Initial learnings called for slight refinements of the design brief – e.g. a suggested build log format and an expansion of the project running time from 6 to 7 weeks.
The second experiment (Sample A) serve as our control group and was conducted identical to the pre-study except from the slight revisions mentioned above.
The third experiment was (Sample B) identical to the control group besides a 40 min introduction on how to use the prototyping support tool. The design teams were invited to use the prototyping support tool, but it was not introduced as a requirement for carrying out the design challenge.

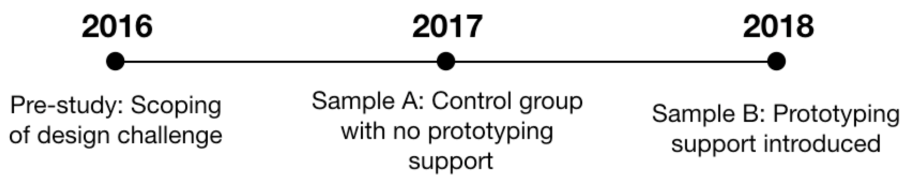



*Figure 3 Overview of the three iterations of the design experiment. Only the results from respectively 2017 and 2018 are made subject to evaluation in this study.*

### 3.2.3 Design challenge and context

At the start of the project all participants were given the same project description, in which they are asked to design and fabricated a speaker, while utilizing digital fabrication technologies. The project description included a short introduction and a list of five project deliverables. An abbreviated version is presented in Figure 4 below:

> "The world stands on the precipice of a fully-fledged digital lifestyle and previously unobtainable technology is accessed through people's fingertips. … Even the physical is able to be manufactured with the use of digital fabrication. … For this project we have partnered with Bang & Olufsen Create. Create is a movement within Bang & Olufsen, with a mission to inspire and be inspired by the global creative community. … You will explore, design and fabricate a 3D printed speaker to see how far you can take the concept of a digitally manufactured loudspeaker…
> Your tasks are to:
> 1. **To design and fabricate a 3D printed loudspeaker** that adds value to the consumer via digital fabrication…
> 2. **To optimize design criteria** such as functionality, aesthetics, acoustics, assembly and design for manufacture…
> 3. **Document your design process** by keeping a build log (project blog). Present your pictures, diagrams, illustrations, prototypes and videos; arguing and discussing about all the design decisions you make. Document various iterations of your designs, design revisions and all other relevant things. You will be using your blog for this as frequent as possible…
> 4. **Provide final Design overview** of your speaker including guidance to replicate your designs…
> 5. **Provide a final reflection** on your project and the design process in your build log…"

*Figure 4 Abbreviated version of the project description used for the experiment.*

All design teams (Sample A + Sample B) followed the same project description, deadline and the project duration was 7 weeks. In order to accommodate for the long lead times, which can be experienced when sourcing components, the following hardware (also illustrated in Figure 5 below) were handed out to all design teams at the first day of the project:

- Computing unit: Raspberry pi, power adapter and a micro SD card with supportive operating system.
- Drivers: A tweeter and a full-range speaker driver.
- Amplifier: A combined amplifier and digital signal processing unit that connects to the Raspberry Pi.


Stack of Rasberry Pi and HiFi Berry Class-D Amplier

Tweeter by Tymphany

Full Range driver by Tymphany

*Figure 5 Hardware components handed out to all design teams.*

The specific components handed out to the design teams are not considered as limitations and restrictions for the study. Previous studies have documented how restrictions of the solution space can spark creativity and it is further considered a rather realistic situation that design projects are required by the surrounding stakeholders to utilize particular components and manufacturing technologies.

The teaching staff facilitating the project consisted of two academic supervisors with advanced degrees in engineering design and three teaching assistants. Further the design challenge was presented in collaboration with an external Design Engineer from the HiFi company Bang & Olufsen, who articulated the company's interest in finding inspiration in the projects conducted by the students. The Design Engineer further provided a 45 min introductory presentation on acoustics and design of speaker systems. In order to isolate, and to the extent possible, evaluate the effect of the 'Prototyping Planner' the project and process instructions were identical throughout the three iterations. More concretely none of the students received any dedicated instructions or lectures on prototyping exercises, prototyping best practice or particular instructions on prototype development.

The projects were carried out at a University Makerspace, where the design teams were provided 24-hour access to workspace and manual workshop, and access to more delicate machines were offered within regular working hours.

#### 3.2.4 Evaluations Metrics

The evaluations performed in the study seek to investigate two aspects of the design team's projects. Respectively, the perceived effect of 'Prototyping Planner' though survey evaluations and the extent of best practice prototyping principles performed by the individual design teams. This approach draws on aspects of the validation square introduced by Pedersen et al. (Pedersen et al., 2000). The two types of evaluation support the possibility to evaluate both the internal constructs of 'Prototyping Planner' and the frameworks overall usefulness.

**Survey of novice designers**

In order to collect evaluations on 'Prototyping Planner' a survey was conducted with the design teams in the 2018 experiment, sample B. The survey was conducted the week after the project was finalized and 52 survey responses were collected. Participants were offered to answer the survey anonymously, in order to limit the possibility of biased evaluations. The survey covered the three overall themes relevant to assessing a prototyping tool in a product development context, respectively:

- Overall evaluations of the support and its appeal.
- Experiences on product development aspects of using the support.
- Evaluations of the tools ability to nurture development competencies related to prototyping.

The survey further encouraged the participants to provide feedback on respectively positive aspects of the tool and also aspects with room for improvement of the tool. Whenever possible elaborations and examples were encouraged.

In order to assess this open ended feedback, it was coded using qualitative content analysis (Hsieh and Shannon, 2005). The responses from the 52 participants was read carefully, and responses that articulated respectively positive and negative aspects of 'Prototyping Planner' were highlighted. In an open ended process these responses were coded and 9 negative tags (e.g. unclear mode of action, lack of examples, challenges in determining fidelity/resolution) and 14 positive tags (e.g. confidence in activities, clear communication, structured planning) were identified. The responses were then reassessed and tagged, using as many tags as necessary to describe the response. By examining the responses for recurring combinations of three or more tags, patterns in the responses were identified. This was the case for three positive evaluations and four suggested improvement potentials. These evaluations have been included in the results and discussion of this study.

**Evaluation of best practice**
As introduced in Figure 4 a requirement for the design teams was to document the project in a build log. These logs were used to study to what extend the design teams – in the 2017 sample A and 2018 sample B - were applying best practice prototyping principles. This was carried out by independently assessing the build logs of all design teams.

**Build Logs**
The build logs can be considered rich data libraries of product development cases. The overall format of the 20 logs from 2017 and 2018 were considered comparable in format and on average they contained 11 blog posts and 4699 words of text. Further all logs included various pictures, diagrams and illustrations. Finally, build logs also include argumentations and discussions regarding the design decisions made by the design teams. An example of a post extract can be seen in Figure 6 below.

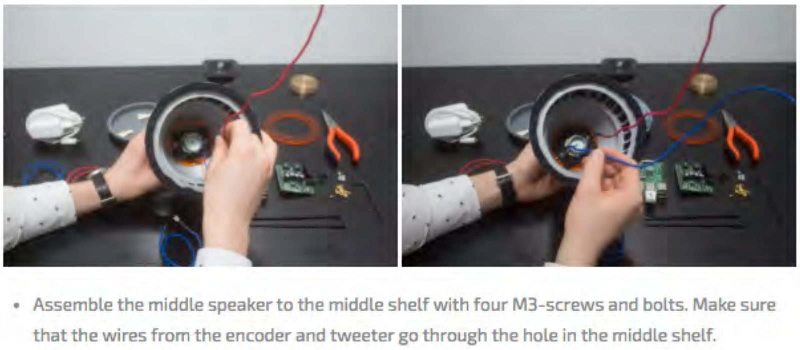



*Figure 6: Example of part of a blog post which describes how to assemble the final speaker design*

**Log assessment**
The build logs were assessed by two independent coders with advanced engineering design degrees. One of the raters was blind to experimental conditions and was not made aware, which build log came from which experimental sample. The second coder participated in the conduction of the study.

The analysis took place as a deductive analysis leveraging a framework on prototyping best practice. The best practice framework originally introduced in a study by Deininger et al. was adopted for this purpose (Deininger et al., 2017). The framework has previously been applied to study best practice in prototyping. The framework provides an overview of 15 prototyping best practice principles, including descriptions and a criterion for rating each best practice principle.

The raters chose to exclude the prototyping principle of interacting with stakeholders, as the experiment was conducted over a short time period and was generally not a design challenge focused on pursuing an external stakeholder need. Rather, the teams were encouraged to focus on product realization and to take the role as engineering and industrial designers, pursuing their team's perception of an attractive product.

Using the framework of prototyping best practice codes, each design team was rated on a 3-point scale:

- 0: Indicated little or no evidence of the behavior.
- 1: Indicated some evidence of an intermediate behavior.
- 2: Indicated evidence that participant's behavior aligned with best practice.

The ratings were based on the extent to which the design team met specific prototyping best practice behaviors. This including the perceived intentionality, level of refinement, mode of construction, iteration, and timing of reported prototyping activities.

Proceeding the coding of the logs, a linear weighted Cohen's kappa [inter-rater reliability for Likert-type scales (Cohen, 1968)] was calculated for sample A and sample B, and obtained respectively 0.42 and 0.43. In both cases this expresses a moderate agreement between the two raters. Initially, the two raters were concerned about this outcome and discussed discrepant coding results. In the majority of cases the discrepancy was identified as routed in slight variations in perceptions of the best practice codes, rather than evaluation of log content. Preceding this dialogue, the coders reached full agreement prior to analysis of the findings.

**Evaluation of design outcome**
A possible third evaluation was to evaluate if the design outcome or final speakers were improved and constituted better products. It was though concluded that other influencing factors would introduce noise and not make such assessment reliable. This e.g. as user satisfaction and perceived value are not easily evaluated by individuals. Recognized consultancies in the domain of hardware entrepreneurship - Predictable Designs (Teel, 2018), Dragon Innovation and Bolt (Einstein, 2015b) - stresses similar reservations regarding early stage assessments of product desirability, and argue that reliable product verification is only possible through sales or preorders.

# 4 Results

In this section we present the result of our analysis and provide further details on our experiment in the light of the research questions presented in section 1. The results are presented in two overall sections. The first is focused on survey data evaluating how the tool was perceived by the design team participants. The second is focused on evaluating the design projects that the design teams conducted and documented in their build logs. The main focus here is on assessing to what extend the teams followed best practice behavior.

## 4.1 Survey of novice designers

This section presents our results of the survey evaluation of 'Prototyping Planner'.

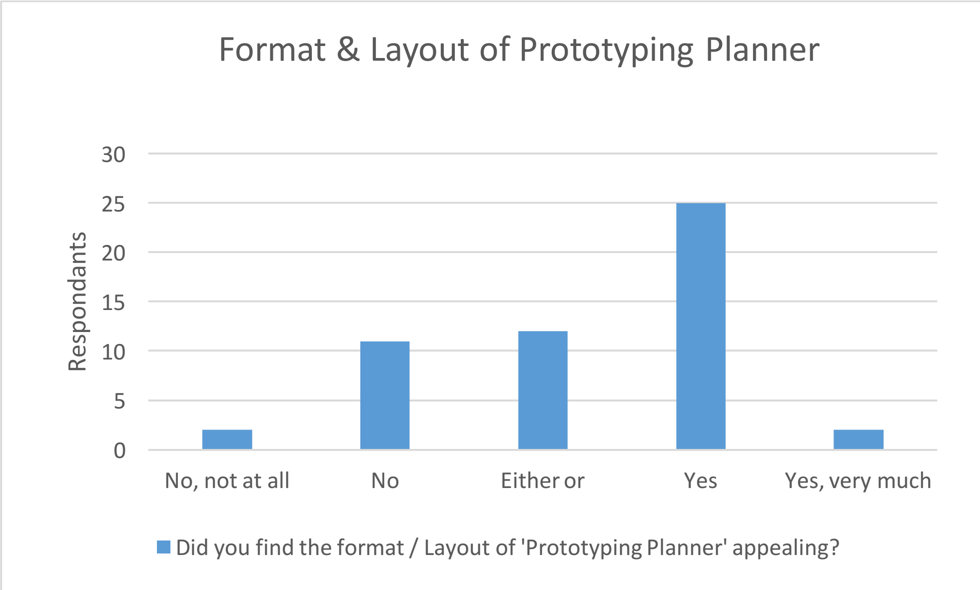



*Figure 7 Evaluation of the format and layout of 'Prototyping Planner'*

Figure 7 outlines that the 'Prototyping Planner' performs well in terms of an appealing format and layout. Such aspects are considered relevant to include as previous studies have shown that dislike towards e.g. academic format of design tools limit their appeal (Araujo, 2001)

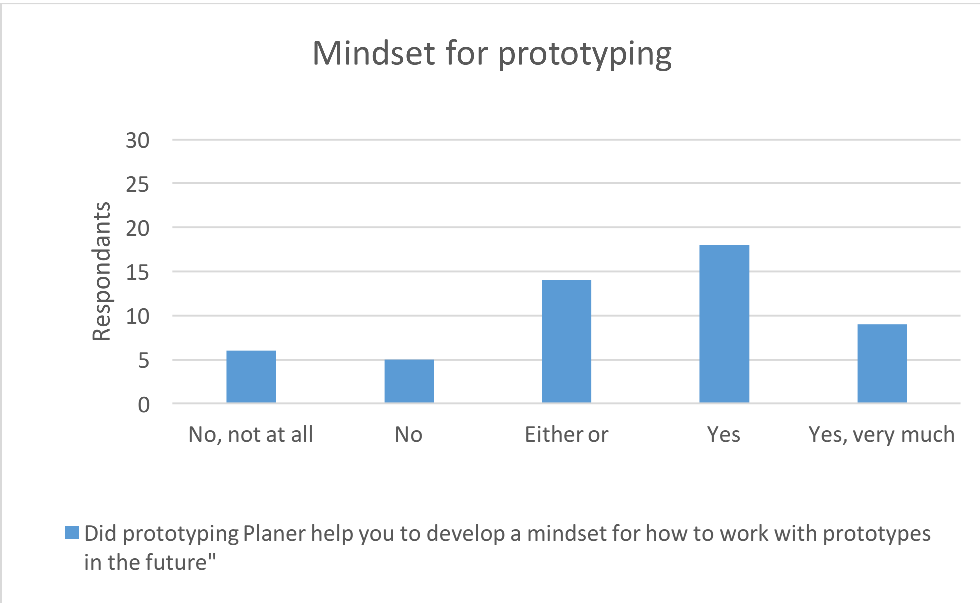



*Figure 8: Evaluation of Prototyping Planners ability to develop a mindset for prototyping*

Figure 8 presents that 'Prototyping Planner' helped the design teams to obtain a mindset for how to work with prototypes in the future. A pleasing finding for the authors, as the experiences of working with 'Prototyping Planner' might help to improve future prototyping practices among students.

### 4.1.1 Process effects

The following section presents results build on the interpretations of pivot tables evaluating respectively to what extend the design teams utilized 'Prototyping Planner' and how they find that the tool helped them in different product development aspects. The pivot table is outlined in Table 3 below.

*Table 3: Pivot tables presenting the relationship between to what extend 'Prototyping Planner' helped to support different product development aspects and to what extend 'Prototyping Planner' was used for the project. All numbers are given in percentage (%)*

| **To what extend did 'Prototyping Planner' help you to:** (1: No, not at all – 5: Yes, Very much) | **To what extend did you use 'Prototyping Planner' in this project?** (1: Not at all – 5: For every prototyping activity**)** | | | | | |
|---|---|---|---|---|---|---|
| **[Define a design problem]** | 1 | 2 | 3 | 4 | 5 | **Total** |
| 1 | 1,92 | 3,85 | 3,85 | 0 | 0 | **9,62** |
| 2 | 3,85 | 9,62 | 13,46 | 3,85 | 0 | **30,77** |
| 3 | 0 | 9,62 | 11,54 | 11,54 | 1,92 | **34,61** |
| 4 | 0 | 1,92 | 7,69 | 13,46 | 0 | **23,08** |
| 5 | 0 | 0 | 1,92 | 0 | 0 | **1,92** |
| **[Plan your activities]** | - | - | - | - | - | - |
| 1 | 1,92 | 3,85 | 3,85 | 0 | 0 | **9,62** |
| 2 | 3,85 | 9,62 | 5,77 | 3,85 | 0 | **23,08** |
| 3 | 0 | 7,69 | 7,69 | 9,62 | 0 | **25,00** |
| 4 | 0 | 3,85 | 17,31 | 15,38 | 1,92 | **38,46** |
| 5 | 0 | 0 | 3,85 | 0 | 0 | **3,85** |
| **[Evaluate results of prototyping]** | - | - | - | - | - | - |
| 1 | 1,92 | 1,92 | 1,92 | 0 | 0 | **5,77** |
| 2 | 1,92 | 7,69 | 7,69 | 1,92 | 0 | **19,23** |
| 3 | 0 | 11,54 | 7,69 | 3,85 | 0 | **23,08** |
| 4 | 1,92 | 3,85 | 15,38 | 13,46 | 0 | **34,61** |
| 5 | 0 | 0 | 5,77 | 9,62 | 1,92 | **17,31** |
| **[Make decisions]** | - | - | - | - | - | - |
| 1 | 1,92 | 5,77 | 1,92 | 1,92 | 0 | **11,54** |
| 2 | 1,92 | 9,62 | 9,62 | 3,85 | 0 | **25,00** |
| 3 | 1,92 | 7,69 | 15,38 | 7,69 | 0 | **32,69** |
| 4 | 0 | 1,92 | 11,54 | 13,46 | 1,92 | **28,85** |
| 5 | 0 | 0 | 0 | 1,92 | 0 | **1,92** |
| **[Gain confidence in what activities to carry out]** | - | - | - | - | - | - |
| 1 | 1,92 | 5,77 | 1,92 | 0 | 0 | **9,62** |
| 2 | 3,85 | 7,69 | 3,85 | 5,77 | 0 | **21,15** |
| 3 | 0 | 7,69 | 15,38 | 3,85 | 0 | **26,92** |
| 4 | 0 | 3,85 | 15,38 | 15,38 | 1,92 | **36,54** |
| 5 | 0 | 0 | 1,92 | 3,85 | 0 | **5,77** |
| **[Communicate with your team]** | - | - | - | - | - | - |
| 1 | 3,85 | 5,77 | 1,92 | 1,92 | 0 | **13,46** |
| 2 | 1,92 | 9,62 | 3,85 | 9,62 | 0 | **25,00** |
| 3 | 0 | 9,62 | 28,85 | 7,69 | 0 | **46,15** |
| 4 | 0 | 0 | 3,85 | 7,69 | 1,92 | **13,46** |
| 5 | 0 | 0 | 0 | 1,92 | 0 | **1,92** |
| **Total** | **5,77** | **25,00** | **38,46** | **28,85** | **1,92** | **100,00** |

From evaluating the results presented in Table 3 an overall observation is that the results are affected by the extent to which the tool is used. The cross tabulated results show that 3 (5,77 %) respondents did not use the tool at all, and in spite of this, provide the most critical feedback. Further the general pattern is that the evaluations tend to be more positive the more the tool has been used for the project. This can be considered a finding of its own, and is a topic we will further elaborate on in the discussion.

The majority of the participants evaluated that ‘Prototyping Planner’ was not sufficient support in defining a design problem. An unfortunate outcome, as defining the most pressing design problems to tackle must be considered a fundamental aspect in product development and prototyping activities.
One possible explanation, is that identification of relevant design parameters is particularly difficult. A observation also identified in previous prototyping studies (Schork and Kirchner, 2018) (Jensen et al., 2018b).

67% of the participants evaluated neutral or positive support in terms of planning their activities. One participant stated that *“The tools help you segment your project and to define specific project tasks”* essentially stating that ‘Prototyping Planner’ provided support in the teams focus and planning of the prototyping process.

75 % of the participants evaluated neutral or positive support in helping them evaluate the results of their efforts. *“’Prototyping Planner’ makes you reflect on what it actually is you want to obtain through your prototyping activities.”* It is our interpretation that ‘Prototyping Planner’ helped the teams to balance the fidelity or resolution of their prototypes in relation to what kinds of evaluations they were performing.

The evaluation of the tool is somewhat inconclusive when it comes to its performance in supporting decision making. This is a topic that we will further address in the discussion.

The majority, evaluates that the tool helped them gain confidence in what activities to carry out. *“You get the right mindset and remember to take into account relevant conditions for every given prototype. This makes you more confident that you have thought the process through.* Focus on structure and process seems to be positively evaluated.

The tool was not able to support communication within the design teams. It is not possible to elaborate why from just assessing the survey data. One explanation might be that the communication takes place through the prototype rather than the tool.

### 4.1.2 Would you use ‘Prototyping Planner’ again?

Part of the survey evaluated if participants would be interested in using ‘Prototyping Planner’ again for respectively professional and student projects.

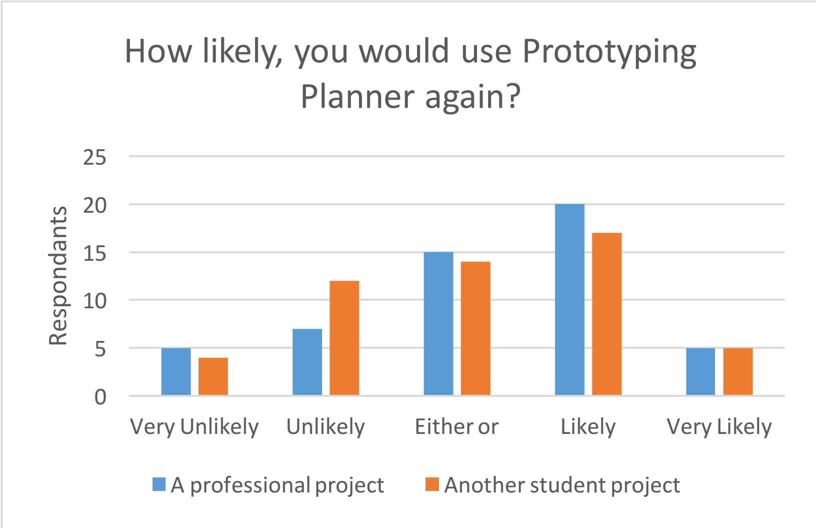



*Figure 9: Evaluation of how likely 'Prototyping Planner' will be used again in a future project.*

The majority of the design teams find it likely that they would use the tool again. There is a slight overrepresentation in respondents who find it likely that they would use the tool in a professional context rather than educational, however not large enough to draw any conclusions.

## 4.2 Evaluation in prototyping best practice

The following sections present the results of evaluating best practice in prototyping documented in the build logs of the design teams. Table 4 introduces the overall results and presents sample A and sample B categorized in the three different categories:

- 0: Little to no evidence of behavior
- 1: Some evidence of an intermediate behavior
- 2: Indicated evidence that participant's behavior aligned with best practice

Further Table 4 presents average values of the two samples, which are derived from the following equation:

$$Avg = \frac{f_{Best\ Practice} * B_{category}}{n_{design\ teams}}$$

Where, $f_{Best\ Practice}$ is the number of design teams in a sample that performs a particular form of best practice. $B_{category}$ is the different categories, 0, 1 or 2 and $n_{design\ teams}$ is the number of design teams in the sample.

The overall finding of evaluating the build logs is that the logs from sample B showed significantly better results in terms of applying prototyping best practice. By comparing the average ratings of the two samples; A 2017 and B 2018, in a T-test it was found that the best practice behavior overall improved significantly (P > 0,00001, CI=0,95).

*Table 4: Results of the interrater evaluation of the best practice behavior applied by the design teams in sample A2017 and B2018.*

| Best Practice Principle | Sample | 0 | 1 | 2 | Avg. 2017 | Avg. 2018 |
|---|---|---|---|---|---|---|
| 1. Design the minimal model needed | A: 2017 | 3 | 5 | 2 | 0,9 | |
| | B: 2018 | 0 | 5 | 5 | | 1,5 |
| 2. Develop prototypes of multiple concepts in parallel | A: 2017 | 5 | 3 | 2 | 0,7 | |
| | B: 2018 | 3 | 3 | 4 | | 1,1 |
| 3. Identify, prioritize, and isolate functional blocks of prototypes | A: 2017 | 0 | 9 | 1 | 1,1 | |
| | B: 2018 | 0 | 5 | 5 | | 1,5 |
| 4. Reassemble blocks into complete concept models | A: 2017 | 0 | 6 | 4 | 1,4 | |
| | B: 2018 | 0 | 6 | 4 | | 1,4 |
| 5. Use appropriate types of prototypes to address specific design questions | A: 2017 | 4 | 6 | 0 | 0,6 | |
| | B: 2018 | 0 | 0 | 10 | | 2 |
| 6. Use inexpensive prototypes early and efficiently | A: 2017 | 3 | 6 | 1 | 0,8 | |
| | B: 2018 | 0 | 1 | 9 | | 1,9 |
| 7. Use prototyping iteratively and develop increasingly refined prototypes | A: 2017 | 2 | 6 | 2 | 1 | |
| | B: 2018 | 0 | 0 | 10 | | 2 |
| 8. Use prototypes to answer specific design questions | A: 2017 | 5 | 4 | 1 | 0,6 | |
| | B: 2018 | 0 | 2 | 8 | | 1,8 |
| 9. Use prototypes to communicate design concepts | A: 2017 | 1 | 8 | 1 | 1 | |
| | B: 2018 | 0 | 8 | 2 | | 1,2 |
| 10. Use prototypes to define design problems | A: 2017 | 5 | 4 | 1 | 0,6 | |
| | B: 2018 | 0 | 6 | 4 | | 1,4 |
| 11. Use prototypes to refine design problem definitions | A: 2017 | 6 | 4 | 0 | 0,4 | |
| | B: 2018 | 0 | 7 | 3 | | 1,3 |
| 12. Use prototypes to test concepts | A: 2017 | 1 | 6 | 3 | 1,2 | |
| | B: 2018 | 0 | 0 | 10 | | 2 |
| 13. Use readily accessible and applicable existing objects or combinations of objects as prototypes | A: 2017 | 4 | 3 | 3 | 0,9 | |
| | B: 2018 | 0 | 0 | 10 | | 2 |
| 14. Vary the scale of prototypes | A: 2017 | 5 | 4 | 1 | 0,6 | |
| | B: 2018 | 3 | 5 | 2 | | 0,9 |

By evaluating the dynamics in "Little or no evidence of best practice", we observe improvement or on pair performance on all best practice principles after implementing the tool. Essentially this gives the indication that the average level of prototyping activities was improved throughout the design teams.

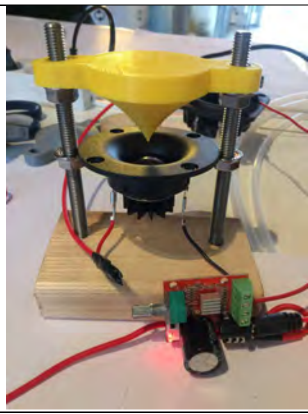
When evaluating what best practice principles were improved the most, we observe that the four principles (respectively 5, 6, 8, and 13) were elevated by a value 1,0 or higher.
A pattern in these four principles are that principle 5 and 8 concerns the ability to define an adequate fidelity / resolution of prototypes and use them effectively on a focused/specific deign question. Principle 6 and 13 share the ability to identify possibilities for making cost effective prototypes. This in some cases through readily available objects and also by doing it early in the development process.

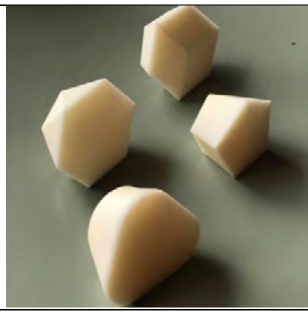
The least improvements were observed for principle 4, 9 and 14 which were all elevated by 0,03 or lower. The immediate interpretation of this result is that the tool is not providing strong support to nurture these principles. Other potential reflections can also be that the design challenge might not by ideal for working with; 1 Scaled prototypes due to the size of the speakers which are optimized for desktop digital fabrication tools. 2; The product is highly integrated and a more modularized product could increase the possibility to observe differences in the process of reassembling blocks of prototypes into complete concept models. A last reflection on these results are that the principles of using prototypes for communication is not easily evaluated from the material presented in the build logs, and is hereby a potential limitation for the study.

### 4.2.1 Characteristic examples of best practice

In order to support the contextual understanding of the design project and the prototyping activities we highlight four representative cases of best practice prototyping activities carried out by the design teams in Sample B. The examples are presented in Table 4 below.

*Table 5 Examples of best practice performed by design teams in sample B.*

| **Best Practise Examples** | |
|---|---|
| **Best Practise applied** | **Representative Picture** |
| **Example A** | |
| Best practice applied:<br>- Design the minimum model needed.<br>- Use prototypes to answer specific design questions. | <br> |
| **Example B** | |
| Best Practice: Use prototypes to define design problems |  |
| **Example C** | |

| | |
|---|---|
| Best practice applied:<br>- Use readily accessible and applicable existing objects or combinations of objects as prototypes. |  |
| **Example D** | |
| Best practice applied:<br>- Vary the scale of prototypes<br>- Develop prototypes of multiple concepts in parallel |  |

Example A: In the process of designing the hinge mechanism for a sliding cover, the design team started out by making fast 3d printed iterations with the objective to dimension the interlocking interfaces. A relevant exercise as neat tolerances were needed to obtain a snug fit on the main assembly of the speaker housing.

Example B: An important aspect of a speaker design is how the soundwaves are distributed from the design. A way to obtain an omnidirectional sound effect is by utilizing cone shaped acoustic lenses. In order to understand and determine the effects of the acoustic lens at varying distance above the tweeter, a simple test rig was fabricated.

Example C: Simple cardboard box was fabricated to explore acoustic properties of a particular size and shape of a design concept.

Example D: In order to early explore geometric aesthetics a design team performed parallel prototyping of different design concept through scaled prototypes in order to effectively explore the performance of the different principal structures.

## 5 Discussion

In this section we present a discussion of our results in the light of our research questions. ‘Prototyping Planner’ is a work in progress framework and in that regard we dedicate a significant part of the discussion to reflections on how ‘Prototyping Planner’ could be further developed. Finally, we outline opportunities for further work.

## 5.1 Overall evaluation

From evaluating the results of this study, we find that there – with further development – are high potentials in the implications of prototyping frameworks like 'Prototyping Planner'. From the existing literature we know that billions of dollars are each year wasted on products that fail in the market (Cooper, 2001), and well executed prototyping might be a company's most valuable tools for navigating their development projects to success.

## 5.2 Positive aspects of the tool

By evaluating the qualitative feedback three codes for feedback on well-functioning aspects of 'Prototyping Planner' was defined. The codes are presented in Table 6.

*Table 6 Coded qualitative feedback on positive aspects of 'Prototyping Planner'*

| ***What aspects of 'Prototyping Planner' worked well?*** | | |
|---|---|---|
| **Code** | **Example** | **Incidents** |
| Supports communication in design team. | "The tool helped our design team talk through our prototyping activities and obtain a shared understanding." | 4 |
| Supports clarification of purpose and intention of prototyping. | "The tool makes you reflect why you prototype and how you can most optimally prototype your design challenges." | 7 |
| Supports planning and confidence in what activities to carry out. | "Makes you think your upcoming work through, make you think structured and account for all the steps in the prototyping process." | 10 |

### 5.2.1 Support in communication

The feedback by four respondents were coded to particularly articulate that 'Prototyping Planner' supports communication in the design team. This is somewhat contradictory the results presented in the pivot table (Table 3), where communication support received the lowest score of the evaluated parameters. In the results we presented the reflection that of using prototypes for communication is not easily evaluated from the material presented in the build logs, this is however not the case for the surveys where the respondents could directly evaluate design team communication. 'Prototypes for communication' among novice designers is a topic which has previously received some interest. Previous studies have particularly outlined how novice designers seem to only possess a limited understanding of how prototyping can be applied and utilized for communication purposes (Lauff et al., 2017), (Deininger et al., 2017), (Menold et al., 2017). The finding that 'Prototyping Planner' did not show promising results in supporting this practice is hereby an indicator that similar and related support tools are not sufficient in nurturing this practice among novice designers.

### 5.2.2 Clarification of purposes

7 respondents articulated that 'Prototyping Planner' helped them to reflect on why they prototype and how they can most optimally prototype their design challenges. We consider this an important impact of the tool as it concerns a vital element in adopting many prototyping best practice principles. Further the finding inline well with improvement potentials of the design practices of novice designers, which have been identified in previous studies. Hostettler et al have underlined how teams of novice designers were actively prototyping, but lacked the ability to concretize the purpose of prototyping. Rather the teams were incrementally approaching their envisioned final product instead of using the prototypes as a method to gain knowledge over partial designs and uncertainties (Hostettler et al., 2017).

### 5.2.3 Support in planning and confidence

The most often occurring code in the qualitative feedback articulated that 'Prototyping Planner' helped to think the upcoming work through and apply a structured approach to take into account 'all' the steps in the prototyping process. This is another important impact of 'Prototyping Planner', as the ability to front load upcoming steps in the prototyping process is essential in determining what prototypes to build in the first place. Essentially you cannot determine the characteristics of the prototype and its fidelity if you do not include considerations on the tests or experiment you intend to conduct. We again find that the finding inline well with improvement potentials of the design practices of novice designers, which have been identified in previous studies. Ahmed et al. e.g. documented how novice designers adopt a process of trial and error, omitting any preliminary evaluation (Ahmed et al., 2003) and Atman et al. found that novice designers generally spend less time in problem scoping and information gathering than design experts (Atman et al., 2007).

## 5.3 How can the framework be improved?

In the following paragraphs we outline our obtained insights on how 'Prototyping Planner' through continued development can be improved. As introduced in our methodology the survey provided the respondents the possibility to provide qualitative feedback on the experiences in using 'Prototyping Planner'. Table 7 below presents the results of this process, and the four codes provides insights that can be transformed into improvement potentials for 'Prototyping Planner'.

*Table 7 Coded qualitative feedback on aspects of 'Prototyping Planner' which could be improved*

| *How can 'Prototyping Planner' be improved?* | | |
|---|---|---|
| **Code** | **Example** | **Incidents** |
| Examples on general best practice for inspiration. | "The tool provides a good process wise support but examples on best practice approaches for inspiration are lacking." | 7 |
| Mode of action was not directly clear. | "How to utilize the tool was not directly clear and further explanations were required." | 4 |
| To comprehensive descriptions. | "The planner is so comprehensive it feels overwhelming and discouraging." | 8 |
| Interactive version of tool or approach for how to transfer results outside tool-sheet. | "More space is required for documentation and it is not ideal to write notes. An interactive or digital version could Invite for more interaction within design team members." | 5 |

The authors find all of these valuable contributions for improving 'Prototyping Planner' as a design support tool.

### 5.3.1 Examples of best practice

Seven requests for 'Examples on general best practice for inspiration' were recorded in the qualitative data presented in Table 5. The authors evaluate that such feedback might relate to a more general demand and lack of available material to support prototyping activities. We find that this might relate to the survey results presented in Table 3, where it was indicated that 'Prototyping Planner' provide limited support in decision-making. Essentially more examples on best practice could provide inspiration for novice designers in their decision making process. To establish libraries of prototyping examples and best practice with the intend to provide inspiration, have also previously been identified as a current need and suggested by (Jensen et al., 2015).

#### 5.3.2 Unclear mode of action

The majority of respondents reported that they found the overall format and layout of ‘Prototyping Planner’ appealing. The feedback from four respondents were though coded to report an unclear mode of action. More concretely this feedback describes that the design teams did not find it clear in which order the steps of the tool was intended to be utilized. While this feedback should be taken into consideration for further development of the tool, the authors did on purpose chose a layout of the tool which was not enforcing the user to follow a sequence of steps. This, as prescriptive guidelines have previously reviewed negative evaluations from novice designers (Daalhuizen et al., 2014), (Person et al., 2012) and further it was the intention to make a tool that could be used more loosely and decoupled than other more prescriptive tools.

#### 5.3.3 Comprehensive descriptions

Eight participants provided the feedback that ‘Prototyping Planner’ is too comprehensive. From cross tabulation we identify that six of these eight participants also registered that they did ‘not at all’ or ‘only to a limited extend’ (rates 1 or 2 on the Likert scale) use ‘Prototyping Planner’ throughout the project. Whereas critical feedback should be acknowledged, the cross tabulation could indicate a more general dislike regarding prescriptive design methods among these particular participants.

#### 5.3.4 Digital and Interactive support tools

Five participants argued that handwritten documentation on printed sheets or digital typewriting on pdf versions of the ‘Prototyping Planner’ tool were not favorable for knowledge sharing and team collaboration. Essentially it can be argued that future support tools are to be ‘born digital’ or to integrate, replicate and function in a digital development environment.

### 5.4 Who chose to use the tool?

The survey results document an approximate normal distribution, in terms of the extent to which ‘Prototyping Planner’ was applied by the design teams. The results also represent a correlation between use of ‘Prototyping Planner’ and the participant’s general opinion and attitude regarding the design tool. Generally, positive evaluations correlate with high adoption of the tool. As the participants filled in the survey in an anonymized manner, we are not able to establish causal arguments on why some teams used the tool to a wider extend than others. The characteristics of individual designers and how it affects preferences in terms of methodology use, has previously been a topic of interest in the design community (Badke-Schaub et al., 2011). Such reflections introduce the possibility that ‘Prototyping Planner’ might not be equally attractive to all ‘types’ of designers. Daalhuizen and Badke-Schaub found that adoption of methodological support among designers, was highly increased in unfamiliar design situations (Daalhuizen and Badke-Schaub, 2011). A hypothesis is, that previous experience and designer self-efficacy of the participants might be determining characteristics in the choice of utilizing ‘Prototyping Planner’. This is further elaborated through the term ‘method mindset’ proposed by Andreasen, who argue that ‘method mindset’ is a prerequisite for use of design methods effectively (Andreasen, 2011). Such ‘method mindsets’ concern both knowledge about understanding the prerequisites for using a method (know-what), and the skills and ability needed to use it effectively (know-how) (Person et al., 2012). When interpreting the evaluation of ‘prototyping mindsets’ presented in Figure 8, the results highlight how such was not a priori a well-established competence of all participants.

## 5.5 Metrics comparison: Best practice and survey results

A discrepancy can be observed in-between the survey results and the elevation in the presence of best practice behavior. Different arguments can describe such discrepancy; Despite all teams working independently, there is still the possibility that crosspollination and inspiration took place, and provided inspiration for prototyping activities. Such would introduce a common lift in the presence of best practice behavior. Another argument relates to preferences in use of design methodology. A central element is here that following prescriptive methodology might increase development quality, but not necessarily provide the same immediate positive experiences for the design teams. Studies have e.g. documented how systematic methods are evaluated as ineffective and unattractive; "systematic method resulted in significantly higher perceived time pressure, lower motivation and higher effort spent." (Daalhuizen et al., 2014)
While limitations and shortcomings of 'Prototyping Planner' should be recognized by the authors, we also argue that 'underdeveloped' 'method mindsets' could negatively affects evaluations. This supported by the statement; Such mindset "do not occur by following a method once or twice but through multiple encounters" (Person et al., 2012, 2012).

Prototyping is an integrated and interwoven product development activity making it a multidimensional and sometimes challenging design activity to master. In this study we have introduced 'Prototyping Planner', and we outline a range of insights on the tool, which seems to provide valuable support for design teams. Other insight, renders further investigation and introduces questions for further discussions and areas are also identified with direct room for improvement and changes of the tool is requested. Such dynamics are unfolded through the 'work in progress' state of the support tool. By acknowledging that best practice in design prototyping is not an exact science and that all development projects can have unique characteristics, we believe that these insights can be of interest to researchers and practitioners who share an interest in prototyping as a design activity.

## 5.6 Opportunities for further work and limitations of study

In this section we reflect on limitations of our study and outline some identified opportunities for further work.

### 5.6.1 Study Limitations

The sample population of our study does not allow for detailed statistical analysis and is a limitation regarding the generalizability of the results. Further the findings relate to the design efforts of novice designers with limited product development experience. Hereby we are unable to generalize the results to e.g. expert designers. We assert that this study is still useful, as elevation of novice designers' competencies are highly relevant.
The experiment conducted was a relatively open design challenge. On a positive note this introduces a realistic test environment, but also introduces limitations for the evaluations which can be performed. Hereby the authors e.g. refrained from evaluating the final design outcomes in terms of different quality or perceived desirability metrics.

### 5.6.2 Improvements of 'Prototyping Planner'

The results of this study invites for further iterations in developing 'Prototyping Planner' and incorporate feedback and insights obtained from conducting the present study. The results are despite their coupling to ‘Prototyping Planner’ also applicable and of relevance to related types of prototyping support.

#### 5.6.3 Further verifications of ‘Prototyping Planner’

The initial layout of ‘Prototyping Planner’ has in this study been verified as a design tool through a controlled experiment. Future evaluations should also include a broader range of attributes and preferably make use of actual use cases. At this point initial verification of the tool has also been performed on industry cases in collaboration with a Seed Stage entrepreneurship accelerator program. The tool received on pair or better evaluations when applied in product development workshops. More comprehensive development activities and structured data collection are though required to provide sufficient material for evaluations on the tools industrial relevance and performance.

#### 5.6.4 Understanding dynamics of best practice

We adopted the best practice principles from Deininger (Deininger et al., 2017). While the list is one of the most comprehensive overviews of prototyping best practice principles, it also has some limitations. A few of the principles prescribes that they should be applied in the early stages of development, but generally no contextual overview, taxonomy or strategic aspects are provided. While there has recently been a growing interest in the topic of prototyping strategies, we do still only have a scattered understanding of the topic (Camburn et al., 2017), (Christie et al., 2012). Future studies could investigate such dynamics further and study design context in which particular practice might be superior.

## 6 Conclusion

This paper presents a controlled experiment, conducted through the participation of 20 teams of novice designers. The experiment focused on the evaluation of a prototyping framework named ‘Prototyping Planner’, with the objective to holistically support designers with limited or intermediate experience in their prototyping activities. The aims of this study was to understand; (i) How a prototyping framework affect the perceived product development process of design teams? and (ii) How a prototyping framework affect the extend of best practice prototyping principles practiced by the design teams?

The first part of the analysis is focused on the participants perceived value of the framework. Main results document that the support tool has an appealing layout and helped the participants in developing a ‘prototyping mindset’. Results also reveals more balanced evaluations of the tools support e.g. in its ability to support team communication. The second part of the results present assessments of build logs created by the design teams. It is highlighted how the use of ‘Prototyping Planner’ lead to significant improvements in the designs teams’ application of prototyping best practice principles; Design teams obtained a more focused prototyping effort and addressed specific design questions rather than trying to comprehend the whole product. A discrepancy can be observed between the participant’s evaluation of the tools performance and the elevation in best practice prototyping observed. Authors acknowledge improvement potentials of the framework, but also hypothesize this could be rooted in negative perceptions of prescriptive support tools and lacking ‘method mindsets’ among participants.

The results of this study provides empirical insights on the dynamics of a prototyping framework, but the study can also be used as probe for further exploitation of design prototyping. The authors believe that these insights can be of interest to both practitioners and other researchers who share an interest in performing best practice prototyping activities.

## Acknowledgements

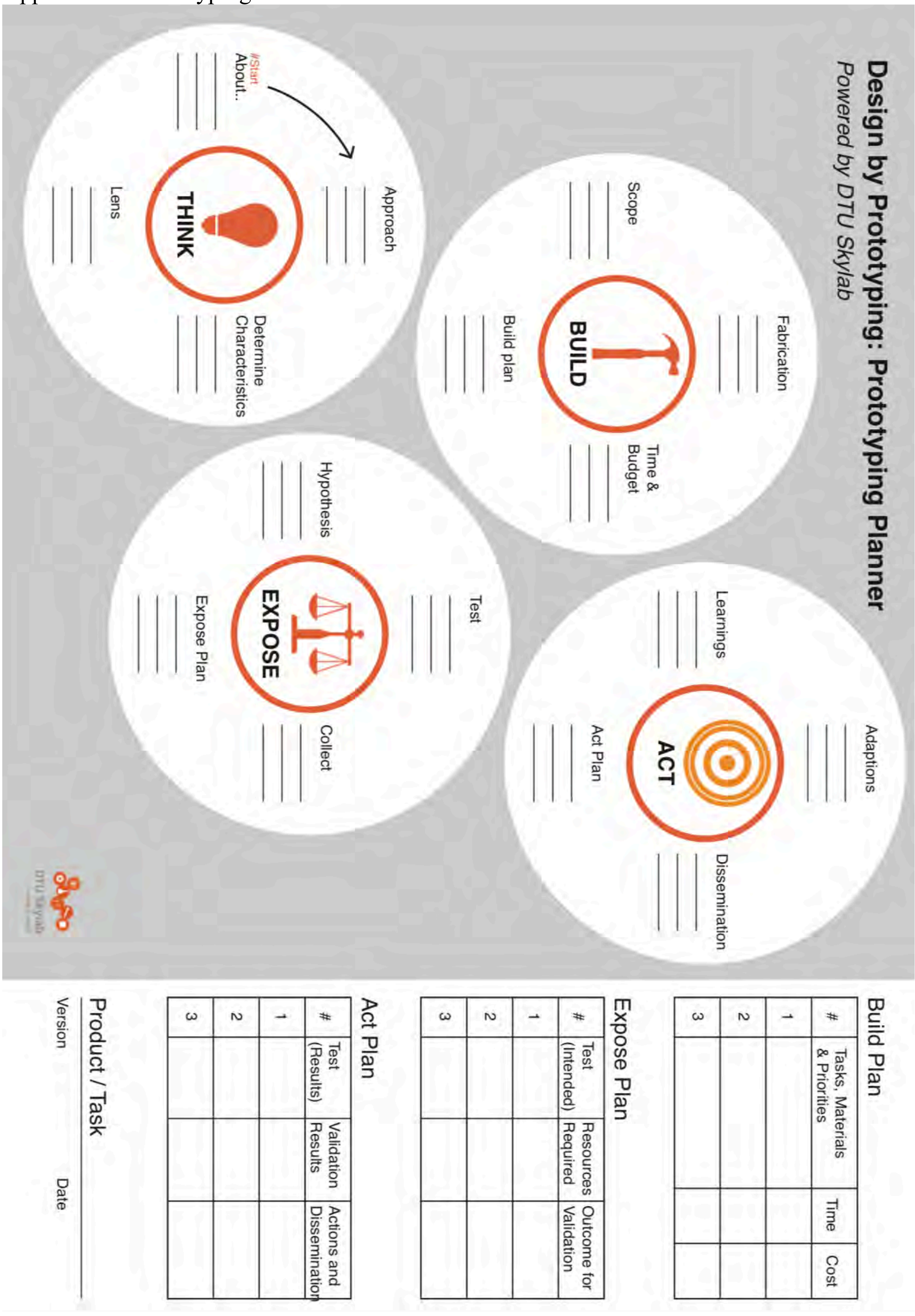
The authors would like to thank all participants in the study for the enthusiasm and creativity that they committed to the design projects.

## References

Ahmed, S., Wallace, K.M., 2004. Identifying and supporting the knowledge needs of novice designers within the aerospace industry. J. Eng. Des. 15, 475–492. https://doi.org/10.1080/09544820410001708430
Ahmed, S., Wallace, K.M., Blessing, L.T., 2003. Understanding the differences between how novice and experienced designers approach design tasks. Res. Eng. Des. 14, 1–11.
Andreasen, M.M., 2011. 45 Years with design methodology. J. Eng. Des. 22, 293–332.
Araujo, C.S., 2001. Acquisition of product development tools in industry: A theoretical contribution. Technical University of Denmark, DTU, Lyngby,.
Atman, C.J., Adams, R.S., Cardella, M.E., Turns, J., Mosborg, S., Saleem, J., 2007. Engineering Design Processes: A Comparison of Students and Expert Practitioners. J. Eng. Educ. 96, 359–379. https://doi.org/10.1002/j.2168-9830.2007.tb00945.x
Badke-Schaub, P., Daalhuizen, J., Roozenburg, N., 2011. Towards a designer-centred methodology: descriptive considerations and prescriptive reflections, in: The Future of Design Methodology. Springer, pp. 181–197.
Buur, J., 1989. Design models in mechatronic product development. Des. Stud. 10, 155–162. https://doi.org/10.1016/0142-694x(89)90033-1
Camburn, B., 2015. A Systematic Method for Design Prototyping. J. Mech. Des. 137, 081102. https://doi.org/10.1115/1.4030331
Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., Wood, K., 2017. Design prototyping methods: state of the art in strategies, techniques, and guidelines. Des. Sci. 3, e13. https://doi.org/10.1017/dsj.2017.10
Camburn, B., Wood, K., 2018. Principles of maker and DIY fabrication: Enabling design prototypes at low cost. Des. Stud. 58, 63–88. https://doi.org/10.1016/j.destud.2018.04.002
Camburn, B.A., Dunlap, B.U., Kuhr, R., Viswanathan, V.K., Linsey, J.S., Jensen, D.D., Crawford, R.H., Otto, K., Wood, K.L., 2013. Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment, in: ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, p. V005T06A033–V005T06A033.
Christie, E.J., Jensen, D.D., Buckley, R.T., Menefee, D.A., Ziegler, K.K., Wood, K.L., Crawford, R.H., 2012. Prototyping Strategies: Literature Review and Identification of Critical Variables, in: American Society for Engineering Education. American Society for Engineering Education.
Cohen, J., 1968. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. Psychol. Bull. 70, 213–220. https://doi.org/10.1037/h0026256
Cooper, R.G., 2001. Winning at New Products, Accelerating the Process from Idea to Launch, 2001. Camb. Perseus.
Cross, N., 2008. Engineering design methods : strategies for product design. John Wiley & Sons.
Daalhuizen, J., Badke-Schaub, P., 2011. The use of methods by advanced beginner and expert industrial designers in non-routine situations: a quasi-experiment. Int. J. Prod. Dev. 15, 54–70. https://doi.org/10.1504/IJPD.2011.043661
Daalhuizen, J., Person, O., Gattol, V., 2014. A personal matter? An investigation of students' design process experiences when using a heuristic or a systematic method. Des. Stud. 35, 133–159. https://doi.org/10.1016/j.destud.2013.10.004
Deininger, M., Daly, S.R., Sienko, K.H., Lee, J.C., 2017. Novice designers' use of prototypes in engineering design. Des. Stud. 51, 25–65. https://doi.org/10.1016/j.destud.2017.04.002
Deming, W.E., 1986. Out of the Crisis. Cambridge University Press.
Einstein, B., 2015a. The Illustrated Guide to Product Development (Part 1: Ideation) [WWW Document]. Bolt Blog. URL https://blog.bolt.io/the-illustrated-guide-to-product-development-part-1-ideation-ab797df1dac7#.harn8xqx4 (accessed 11.22.16).
Einstein, B., 2015b. Kickstarter != Product/Market Fit [WWW Document]. Bolt Blog. URL https://blog.bolt.io/kickstarter-product-market-fit-95f2b13ae75f#.dy6ji1231 (accessed 11.22.16).

Hostettler, R., Böhmer, A., lindemann, udo, knoll, alois, 2017. TAF Agile Framework.
Hsieh, H.-F., Shannon, S.E., 2005. Three approaches to qualitative content analysis. Qual. Health Res. 15, 1277–1288.
Jensen, L.S., Nissen, L., Bilde, N., Özkil, A.G., 2018a. PROTOTYPING IN MECHATRONIC PRODUCT DEVELOPMENT: HOW PROTOTYPE FIDELITY LEVELS AFFECT USER DESIGN INPUT. Presented at the 15th International Design Conference, pp. 1173–1184. https://doi.org/10.21278/idc.2018.0415
Jensen, L.S., Özkil, A.G., Mougaard, K., 2016. Makerspaces in Engineering Education: A Case Study. Proc. Asme Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf. Vol 3.
Jensen, L.S., Vorting, D., Villadsen, A., Molleskov, L.H., Ozkil, A.G., 2018b. Prototyping for Desirability by Design of Experiments: A Case Study of a Hardware Startup 10.
Jensen, M.B., Balters, S., Steinert, M., others, 2015. MEASURING PROTOTYPES-A STANDARDIZED QUANTITATIVE DESCRIPTION OF PROTOTYPES AND THEIR OUTCOME FOR DATA COLLECTION AND ANALYSIS, in: DS 80-2 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 2: Design Theory and Research Methodology Design Processes, Milan, Italy, 27-30.07. 15.
Kelley, T., Littman, J., 2001. The art of innovation : lessons in creativity from IDEO, America's leading design firm. Currency/Doubleday.
Lauff, C., Kotys-Schwartz, D., Rentschler, M.E., 2017. Perceptions of Prototypes: Pilot Study Comparing Students and Professionals. ASME, p. V003T04A011. https://doi.org/10.1115/DETC2017-68117
Menold, J., Jablokow, K., Simpson, T., 2017. Prototype for X (PFX): A holistic framework for structuring prototyping methods to support engineering design. Des. Stud. 50, 70–112.
Menold, J., Simpson, T.W., Jablokow, K., 2018. The prototype for X framework: exploring the effects of a structured prototyping framework on functional prototypes. Res. Eng. Des. 1–15. https://doi.org/10.1007/s00163-018-0289-4
Menold, J., Simpson, T.W., Jablokow, K.W., 2016. The Prototype for X (PFX) Framework: Assessing the Impact of PFX on Desirability, Feasibility, and Viability of End Designs. ASME, p. V007T06A040. https://doi.org/10.1115/DETC2016-60225
Otto, K.N., Wood, K.L., 2003. Product design: techniques in reverse engineering and new product development. Prentice-Hall.
Ozkan, O., Dogan, F., 2013. Cognitive strategies of analogical reasoning in design: Differences between expert and novice designers. Des. Stud. 34, 161–192. https://doi.org/10.1016/j.destud.2012.11.006
Özkil, A.G., 2017. Collective design in 3D printing: A large scale empirical study of designs, designers and evolution. Des. Stud. 51, 66–89. https://doi.org/10.1016/j.destud.2017.04.004
Pedersen, K., Emblemsvag, J., Bailey, R., Allen, J.K., Mistree, F., 2000. Validating design methods and research: the validation square, in: ASME Design Engineering Technical Conferences. pp. 1–12.
Person, O., Daalhuizen, J., Gattol, V., 2012. Forming a Mindset: Design Students' Preconceptions about the Usefulness of Systematic Methods, in: DS 74: Proceedings of the 14th International Conference on Engineering & Product Design Education (E&PDE12) Design Education for Future Wellbeing, Antwerp, Belguim, 06-07.9.2012.
Schmidt, T., Wallisch, A., Böhmer, A., Paetzold, K., Lindemann, U., 2017. Media Richness Theory in Agile Development: Choosing Appropriate Kinds of Prototypes to Obtain Reliable Feedback.
Schork, S., Kirchner, E., 2018. METHOD FOR THE DEVELOPMENT OF EARLY PROTOTYPES OF MECHATRONIC MACHINE ELEMENTS BASED ON THEIR CRITICAL PROPERTIES. Presented at the 15th International Design Conference, pp. 1325–1336. https://doi.org/10.21278/idc.2018.0343
Smith, R.P., Leong, A., 1998. An Observational Study of Design Team Process: A Comparison of Student and Professional Engineers. J. Mech. Des. 120, 636–642. https://doi.org/10.1115/1.2829326
Teel, J., 2018. 10 Lessons I Learned Bringing My Own Product to Market. Predict. Des.
Ulrich, Eppinger, 2007. Product design and development. McGraw-Hill Higher Education.
Viswanathan, V., Atilola, O., Goodman, J., Linsey, J., 2014. Prototyping: A key skill for innovation and life-long learning, in: 2014 IEEE Frontiers in Education Conference (FIE) Proceedings. Presented at the 2014 IEEE Frontiers in Education Conference (FIE) Proceedings, pp. 1–8. https://doi.org/10.1109/FIE.2014.7044423
Wall, M.B., Ulrich, K.T., Flowers, W.C., 1992. Evaluating prototyping technologies for product design. Res. Eng. Des. 3, 163–177.

Appendix 1: 'Prototyping Planner' Front side



Appendix 1: 'Prototyping Planner' back side

# Design by Prototyping: Prototyping Planner

*Powered by DTU Skylab*

Design by Prototyping V. 1.0 2018
Jensen, S. Lasse & Özkil, G. Ali
lsje@dtu.dk & alio@dtudk
DTU Skylab & DTU Mechanical Engineering
Technical University of Denmark

## Introduction

### What?

Design by prototyping is a product development paradigm which has prototypes and prototyping activities as the center of activities. Two primary support tools define the paradigm. The first tool is the 'Design by Prototyping development model'. The model represents four different domains of prototypes which in combination support the process of incubating an early stage idea and transforming it into a product that can be both mass manufactured and address a market need.
The second support tool is called 'Prototyping Planner' and works as a four step model to aid the concrete planning and execution of prototyping activities.

### Why?

Prototypes has a long history in product development but recent developments in digital fabrication, reconfigurable electronics and open design platforms provides new opportunities that exceeds previous barriers in "what", "when" and "how much" is it viable to prototype.
The philosophy behind Design by Prototyping is to combine best practices from established hardware and mechatronic product development methodologies with fast agile methods inspired by the software domain. Design by Prototyping intends to support your project with the philosophy that "To build ***it*** beats talking about ***it***." And "Results and data beats opinions."
We want to help you "Building the right ***it*** before you build ***it*** right."

### How?

Design by prototyping is particularly attractive to small development teams that have limited experience in prototyping of tech hardware. We advise to read through these guidelines before you start using the tools.

The 'Design by prototyping development model' intends to help you navigate your overall product development process.
Start your process with the development model to identify a focus in one of the four prototyping domains. Identify a focus based on the largest project uncertainty. When a focus is identified, utilize prototyping planner and go through the four steps of the model for concrete planning and execution of prototyping activities.
Remember to document findings. Consider a design specification or to communicate your result thorough further prototyping activities

## Think

### About

Prototyping Planner is made with the objective to support you in your concrete prototyping activities. Go through the four steps of the model – ***Think***, ***Build***, ***Expose***, ***Act*** – in a iterative way to generate insights and plan your prototyping activities.
The first step, ***Think*** represent reflective points about prototyping, ***Build*** considers the resources needed to fabricate prototypes, ***Expose*** concerns the use of prototypes, whether they are made for concrete testing or communication to relevant stakeholders. ***Act*** focuses on insight from prototyping and next steps.

You might go over the model a few times to get it right. Share the activities with your team and document the process and results to help idenigy your next steps

### Approach

At a overall level prototyping will have an objective that is either divergent or convergent (Figure 1). Respectively meaning that one is either working to create alternatives or working to draw conclusions or choices on known alternatives . Divergent prototyping activities often allow for rough and less refined prototypes in terms of time resources needed to fabricate them. Convergent prototyping activities often requires a more specific and focused effort.
A way to define your ptotyping apprach is through the statement: "Design question drives design medium."
**What medium(s) could suit your design question?**

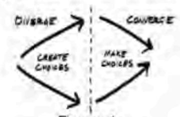



Figure 1

### Determining Characteristics

For a prototype to articulate any 'statement strength' is must have some shared characteristics with the future product or service being designed (Figure 2). Best practise is to build what you need for obtaining satisfactory statement strength, but do not build more than necessary.
**What shared characteristics can you create for your prototype?** Does they allow for generating suitable/relevant insights from exposing the prototype?

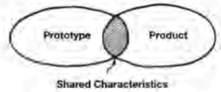



Figure 2

### Prototyping Lens

Similar prototypes can generate different design insights dependent on how they are exposed and what data is being collected from the activity. Human Centered Design Research have previously differentiated between the three lenses ***Desirability***, ***Feasibility*** and ***Viability***. Desirability concerns if the product or service is attractive to the user? Feasibility concerns technologically & engineering. Viability focuses on business perspectives. **What lenses does your prototyping cover?** Could you use the differentiation to focus your efforts more? (Figure 3)

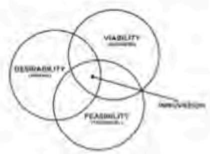



Figure 3

## Build

### Scope

Prototypes can vary from a single part to an entire system. Best practice in Prototyping often has a narrow and well defined focus. A general rule of thumb is that no prototype should be made with higher complexity than what is needed to explore or verify the design question at hand. So don't try to reinvent the wheel. In many cases you can also benefit from hacking and reverse engineering existing products as part of your prototyping activities. **Can you scale your prototype to not include the full design? What functionality is strictly required? What form or fit?**

### Fabrication

How will prototypes be fabricated? As a in house activity? Or will the fabrication be outsourced? Do you have access to the necessary tools and equipment?

Do you have the knowledge and experience? Or necessary fabrication support? What documentation (drawings, calculations, design specifications) might be needed? Will you use the same or different materials than for the final design? What about the manufacturing and assembly techniques?
**List reflections from these questions**

### Time & Budget

What are the expenses related to fabricating this prototype in terms of cost and time? What budget load will it apply to the overall project?
**List reflections from these questions**

### Build Plan

Think though the questions in this category and **establish a 'Build Plan'** by listing: Materials needed, Priorities of tasks and budget expenses in terms of both time and cost.

## Expose

### Hypothesis or Design Question

Try to define a specific hypothesis or design questions that you want to validate or explore for each prototyping activity. Find inspiration in this formula for crafting a falsifiable hypothesis:

***Falsifiable hypothesis =***
***[Specific Repeatable Action]***
***Will***
***[Expected Measurable Outcome].***

The hypothesis or design questions should be relevant and normally making it more specific improves the process. Even though you might be exploring the solution space it is beneficial to establish a working hypothesis or design question.

### Test

**What test can you conduct to validate or reject your design question or hypothesis in an effective manner?**
Consider how the test can support the prototyping lens you are focusing on and if there is a good match between the statement strength through shared characteristics between the prototype and the future product or service.
Also reflect on some practical aspects, such as; How many times should the test be conducted? How long will it take? What stakeholders, equipment or other requirements will the test include? How valid will the test be?

### Collect

**How will results of the prototyping activity be collected?** Try to think of a format for recording results that are in sync with your hypothesis and the test being conducted. Do you need a spreadsheet? Notes on a piece of paper? A dedicated data-logger with Sensors? Video or audio recordings? Will it after the data is collected be necessary to conduct an analysis to interpret the results?
Without losing focus of the test at hand, also consider how to collect notes on additional insights or ideas generated.

### Expose plan

Think though the questions in this category and establish an **'Expose Plan'** by listing: Intended tests, resources required, outcome of the tests for validation of the hypothesis.

## Act

### Learnings

Visit the results of the expose activities and reflect on **what insights were obtained?** What hypothesis did you seem to validate?
What worked well? Where might further iterations be needed?
What surprised you?
What new questions or ideas raised
Are there limitations or reservations for the statement strength of the results?

### Adaptations

How should the results be interpreted?
**What actions and next step can be defined from the results?**

### Dissemination

**How will the results and generated knowledge be documented and shared among team members?** Would it be relevant to present it in a specific format to specific stakeholders?
Results and knowledge related to a design specification should be documented here. It might however also be beneficial to incorporate the findings in a new prototype with the objective to share knowledge on the current design stage of the project.

### Act Plan

Think though the questions in this category and establish a **'Act Plan'** by listing: Results, validations results, actions and disseminations.

DTU Mechanical Engineering
Section of Engineering Design and Product Development
Technical University of Denmark

Nils Koppels Allé, Bld 404
DK-2800 Kgs. Lyngby
Denmark
Tlf.: +45 4525 6263
Fax: +45 4525 1961

www.mek.dtu.dk

October 2018

ISBN: 978-87-7475-552-4

**DCAMM**
**Danish Center for Applied Mathematics and Mechanics**

Nils Koppels Allé, Bld. 404
DK-2800 Kgs. Lyngby
Denmark
Phone (+45) 4525 4250
Fax (+45) 4525 1961

www.dcamm.dk

DCAMM Special Report No. S256

ISSN: 0903-1685