Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures

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This paper maps and describes how prototypes are used to elicit requirements of unknown unknowns in industry. Eight engineering design companies serve as a dataset for a multi-case investigation. By semi-quantitatively analysing 19 prototypes in terms of functionality, timing, stakeholder involvement and requirement elicitation, we present a wide spectrum of prototype utilizations. However, this broad span leads to misunderstandings of what the term 'prototype' encompasses, hindering exploitation of its full potential. Hence, we introduce the term 'prototrial' that covers functional prototypes utilized in the early stages of the design process, prototypes that effectively elicit unknown unknowns. With this contribution, we encourage introducing mind-sets and behaviours that aim at exploration and learning rather than lean implementation − a prototrial-driven culture.

Keywords: product design, prototypes, design process, unknown unknowns, product development

In recent research on radical innovation, development prototypes are given a considerable role as tangible rapid learning cycles representing the mind-set necessary when developing innovative solutions (Haines-Gadd et al., 2015; Leifer & Steinert, 2012; Marion & Simpson, 2009). IDEO-founder David Kelley asserts he can tell almost anything about a company's new-product-development (NPD) efforts by simply sampling a few prototypes − from the care of the models to the quality of the thinking of the designers (Schrage, 2006).

Research has described prototypes as objects in a design process with designated characteristics and details (Blackler, 2009; Houde & Hill, 1997; Lim, Stolterman, & Tenenberg, 2008; Sefelin, Tscheligi, & Giller, 2003). These sources are describing the prototypes from the designer's perspective and their active considerations when using and creating the prototype.

However, Elverum and Welo (2014) state that this does not explain how organisations currently utilize prototypes. How does the prototype support the

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existing NPD process and what is characteristic for companies that manage to implement rapid prototyping in the early fuzzy front end and not only use prototypes as physical iterations on already well-understood products?

This paper aims to address these questions by analysing eight case studies conducted in different companies representing very different industries, but all fitting into the classical engineering design process (Ulrich & Eppinger, 2008). With this we provide the community with a much-needed industrial perspective on the process of prototyping. Inspired by Tracey and Hutchinson (2016) focussing on uncertainty in the design solutions space, we utilize the framework of requirement elicitation Sutcliffe and Sawyer (2013) describing *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*. We evaluate the performance of nineteen different prototypes used in the eight companies and ask to what degree the prototypes help the companies elicit the different types of requirements.

In the theoretical section, we describe parameters defined by previous researchers as affecting the outcome and role of prototypes. These cover three overall topics: functionality and timing in the design process, stakeholder involvement and requirement elicitation. Followed is a description of the research methodology and the eight case studies.

The analysis presents the evaluation of the nineteen prototypes from the eight case studies and maps their performance regarding the three theoretical topics.

In the Results section, we answer our stated research questions and introduce the new term *prototrial*. This term covers high-functional prototypes utilized in the very early stages of the concept development process yet having low fidelity when it comes to comparing the prototype with the final product. These are nurtured not only by the designers themselves, but also the companies' attitude towards conscious targeting of *unknown unknowns,* and the degree of freedom accorded the designer's stated task. We define such company cultures as *prototrial-driven* cultures.

Our main contribution is a detailed mapping of the various utilizations of prototypes in engineering industries today. Further a call for a narrowing of this broad usage, starting by introducing *prototrials* and *prototrial-driven* cultures.

1 Theoretical framework

1.1 Prototypes and their functionality

A prototype is an initial model built to test a design idea; it is widely used in engineering design, from simple paper prototypes to foam models that closely resemble the final product (Blackler, 2009; Lim, Pangam, Periyasama, &

Aneja, 2006; Lim et al., 2008). Several examples show how levels of functionality influences the outcome of a prototype interaction (Blackler, 2009; Hare, Gill, Loudon, & Lewis, 2013; Lim et al., 2006; Sefelin et al., 2003). Traditionally, a prototype's functionality increases throughout a design process with the understanding of the product (Ulrich & Eppinger, 2008). However, recent innovation research that aim to design radical new innovations stresses the value of creating many different functional prototypes in the so called 'fuzzy front end' of the design process (Dow et al., 2010; Elverum & Welo, 2014; Leifer & Steinert, 2012). These prototypes have low fidelity as regards detail of the overall product, but have high functionality as regards a specific area that one wishes to test. We believe the current industry usage of this particular approach is not yet expounded in literature; thus, we chose *level of functionality* as one of the parameters for describing the identified prototypes in this multi-case study.

The literature covers a wide range of categories, beginning with simple visual mock-ups or sketches with extremely low functionality and aiming at communication (Brandt, 2007). This is followed by Wizard-of-Oz experience prototypes that 'fake' the functionality in order to evaluate the user experience (Buchenau & Suri, 2000). Next is the actual functional or works-like prototype that represents an actual function of the prototype (Koo, Li, Yao, Agrawala, & Mitra, 2014). These prototypes are often used in the latter stages of the product development process (Ulrich & Eppinger, 2008). Finally, the high-functional prototypes that are part of parallel testing processes exploring the solution space of a challenge (Carleton & Leifer, 2009; Dow et al., 2010; Gerstenberg, Sjöman, Reime, Abrahamsson, & Steinert, 2015; Reime, Sjöman, Gerstenberg, Abrahamsson, & Steinert, 2015).

As mentioned, the levels of functionality traditionally increase throughout the process from initial throwaway prototypes to ready-for-production ones (Yang, 2005). Meanwhile, the parallel prototypes with high functionality mentioned by Leifer and Steinert (2012) are used in the early stages of the engineering design process. Moreover, Snider, Culley, and Dekoninck (2013) stress the radically different tasks of an engineering designer in terms of creativity throughout the design process. Hence, there is a need to include a time perspective when evaluating the functionality of the analysed prototypes. Ulrich and Eppinger (2008) present six phases representing the generic new product development process: 1. Planning, 2. Concept development, 3. System-level design, 4. Detail design, 5. Testing and refinement and 6. Production ramp-up. These phases cover the explorative approach in the beginning of a product development process and end with the handover to the production line.

1.2 Different types of stakeholder involvement

Prototypes are also described as supporting external stakeholder involvement, which leads to eliciting requirements in new product development (Bogers &

Horst, 2014; Buchenau & Suri, 2000; Mascitelli, 2000; Terwiesch & Loch, 2004). These cases cover interaction with end-users to understand use context and shape technologies (Björgvinsson, Ehn, & Hillgren, 2010; Buur & Matthews, 2008). In recent years, with the increased focus on holistic solutions, external stakeholders have evolved from end-users to sales staff and people with decision-buying powers. This has supported the evolvement of the user-involving design field outside the companies (Sanders & Stappers, 2008). However, intra-organisational boundaries can also be explored by involving prototypes (Petre, 2004; Song, Thieme, & Xie, 1998). In engineering projects, it is common for people with backgrounds in R&D, production, marketing and management to meet around a prototype (Holford, Ebrahimi, Aktouf, & Simon, 2008). In fact, Petre (2004) states that the best performing engineering teams in his multi-case study were the ones working in multidisciplinary teams communicating naturally with other departments, especially management. The author states that many disciplines become more powerful in the context of a multidisciplinary team, where interdisciplinary interaction amplifies creative potential.

> *The demands of interaction across specialisms can nurture surprises and help engineers 'get out of the box' of familiar thinking, as well as helping them reflect on their own knowledge, reasoning, and processes* (Petre, 2004).

Arising from these references in the literature, we focused on the people interacting with the identified prototypes combined with the notion of requirement elicitation. We defined three contexts of prototype interaction: 1. Internal/Internal: Used in the internal conversation with stakeholders inside the development department; 2. Internal/External: Used in the conversation with stakeholders outside the development department but inside the company; and 3. External/External: Used in the conversation with stakeholders outside the company.

1.3 Prototypes and requirement elicitation

Evaluative, prototypes are tools in the requirement engineering field, which has evolved in the process of designing a good product and covers the process of defining the correct requirements for a given product or service (Nuseibeh & Easterbrook, 2000). Here, engineers can utilise several different tools, including prototypes. They help identify opportunities and challenges regarding a certain product area. Elicitation of the correct requirements is still a challenge, especially when it comes to identifying uncertainties and unforeseeable details (Ramasesh & Browning, 2014). In their paper *Requirements Elicitation: Towards the Unknown Unknowns*, Sutcliffe and Sawyer (2013) define the different types of requirements identified during requirement engineering processes as *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*. These terms are categories of requirements that an engineering designer is looking for during requirement elicitation. *Known knowns* cover articulated and accessible facts. *Known unknowns* are questions the design engineer knows need to be answered in the further development process. *Unknown knowns* deal with the unknown knowledge of the involved stakeholders. It is the design engineer's responsibility to ensure this knowledge is articulated by using different elicitation methods. Lastly, they define *unknown unknowns*, which cover issues and details whose existence and relevance is unknown to the engineering designer. In the context of Tracey and Hutchinson (2016), *unknown unknowns* are defined as ontological uncertainty, which they describe as more complex than other types of uncertainty. *Unknown unknowns,* therefore represent the biggest challenge, as severe consequences can follow when design engineers fail to identify crucial information that turns out to be vital for the success of new products (Ramasesh & Browning, 2014). The challenge of the *unknown unknowns* lies within neither the design engineer nor the specialist immediately are able to identify the presence of *unknown unknowns*, since these are not phenomena of neither tacit nor explicit knowledge. A starting point of eliciting unknown unknowns is for companies to acknowledge the existence of *unknown unknowns* and actively put them into play in the development process (Sutcliffe & Sawyer, 2013). Ramasesh and Browning (2014) suggest 10 approaches to identify *unknown unknowns,* including frequent and effective communication, analysing scenarios, incentivising the discovery of *unknown unknowns* and cultivating a culture of alertness to *unknown unknowns*. Although Ramasesh and Browning (2014) do not mention prototypes as tools in any of the suggested approaches, we believe that physical prototypes have considerable potential in supporting the suggested approaches. However, Sutcliffe and Sawyer (2013) argue that prototypes have a limited potential to elicit *unknown unknowns*. Because of these contradicting observations, we have been particularly interested in investigating whether prototypes help in eliciting requirements in terms of *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*.

1.4 Theoretical summary

To summarise the theoretical section, three questions have been developed to clarify the overall research area:

- How does the prototype functionality affect the type of identified requirement: *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*?
- How does the type of stakeholder involvement affect the identified requirements: *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*?
- How does the prototype help the company discover requirements in terms of *known knowns*, *known unknowns*, *unknown knowns* and *unknown unknowns*?

2 Methodology

This study has been designed according to the theories of Eisenhardt (1989), and will be elaborated in terms of data foundation and analysis in the next sections.

2.1 Data foundation

Elverum and Welo (2014) state that current literature fails in explaining how organisations use prototyping and the prototype as artefacts. This statement was our initial research question. The starting scope was rather broad; however, as Eisenhardt (1989) stresses, the importance of recognising the initial research question is tentative in this type of research and it can be changed throughout the research. Several iterations evolved and, in the end, Sutcliffe and Sawyer (2013) requirement categories were used to sufficiently define the identified prototypes while suggesting and challenging existing descriptions of prototypes.

We prioritised diversity of company profiles to gain general insights. The companies were identified through our network in the Norwegian, Danish and German industries and were chosen by a bottom up approach utilising the possibilities this network allowed. To keep the overall focus, the main criteria when selecting companies included securing the studied process to include design engineers and fitting the classical new product development model (Ulrich & Eppinger, 2008). These criteria, allowed us to investigate assumptions such as the prototyping ability of start-ups vs. better-established companies while retaining the engineering design context. In total, eight companies were chosen. When selecting interviewees, we prioritised employees in the companies' product development department, as they were expected to have knowledge on intended use of prototypes and applied knowledge on how prototypes were used in the daily work. These individuals were identified by asking for employees actively participating in the product development process and not only managing the process. Table 1 provides an overview of each company, including the prototypes chosen for analysis. Furthermore, Appendix I presents each company and their prototyping customs briefly. One company, a German toilet care company, wished to remain anonymous, but has confirmed all information in this work. Appendix II presents each of the 19 prototypes with a brief explanation. Due to confidentiality only 10 of the 19 prototypes are presented with pictures in this paper.

Several data types were utilised while conducting the research. All were qualitative and included one interview protocol as back end focus for the ten interviews. We also designed three artefacts to initiate dialogue to get direct input and feedback on concepts defined in the literature:

Table 1 The eight companies. Abbreviations of the companies are used throughout the paper

Name and product	*Employees*	*Business*	*Interviewees*	*Prototypes used for analysis*
Axtech, Norway (AXT) Designing offshore lifting mechanisms capable of lifting weights from 20 000 to 100 000 kg.	40	Business to business	**One interviewee** Manager of R&D department	1. CAD drawings and sketches, no physical prototypes
PREZIOSO Linjebygg, Norway (PL) Provides services and products to the oil & gas industries	150	Business to business	**One interviewee** Manager of R&D department	2. Smaller models of Lego, wood and cardboard 3. Scaled functional 1:5 or 1:10 prototypes
Scandinavian Business Seating, Norway (SBS) Producing chairs for professional office environments	555	Business to retailers/ business	**Two interviewees** Manager and designer in product development department	4. Cardboard add-on handles to existing office chairs 5. Functional hydraulics test 6. 3D printed handles
Medicologic, Denmark (MED) Consultancy helping customers realise ideas in the medical field	10	Business to businesses/start-ups	**Two interviewees** Managing director Team manger R&D Design engineer	7. A prototype made from a plastic bag and a laminating machine 8. Foam models exploring shapes
ROCKWOOL, Denmark (RW) Develops insulation material for the entrepreneurial industry	8800	Business to business	**One interviewee** Manager of R&D department	9. Water absorbing gabion 10. Huts for Roskilde Festival
Experimentarium, Denmark (EXP) Science Museum designing exhibitions, teaching, and science shows	120	Business to private consumers	**Two interviewees** Project manager Design engineer	11. First prototype made of plastic plate and plastic glass 12. Testing set-up with a BoomBlaster 13. Model of the future Soap Bubble Exhibition
Vaavud, Denmark (VAV) Develops mobile wind-meters utilising a smartphone magnometer.	6	Business to private consumers	**One interviewee** Founder of the company	14. Prototypes in the exploring phase. Cardboard, sketches 15. Fluid mechanic test with 3D printed prototypes
German Toilet Care company (GTC) Develops products for the private consumer toilet care industry.	50 000	Business to private consumers	**Eight interviewees** Global Director Fragrances Senior Manager Product Designer Employee in R&D Fragrances WRF Fragrance Marketing Chemist Production Engineer	16. Prototyping production methods on smaller scale 17. Prototyping shape through sketches 18. Prototyping Power Balls in mouldable soap. 19. Plastic models of Toilet Cleaners

1. An empty timeline;
2. An empty graphical presentation of theoretical prototype terminologies for the participants to fill out; and
3. A graphical representation of which tools are used when prototyping.

These artefacts further supported us in the process of combining research findings with the current body of knowledge. Data collection consisted of ten semi-structured interviews, including seven site visits to the product development departments of the respective companies. One interview was conducted remotely and did not allow for a departmental tour. The average interview length was 74 min. Although data collection and analysis overlapped, a semi-structured interview guide ensured uniform information gathering overall (see Appendix III). This information covered the physical details of the applied prototypes to a more process focus to capture the requirements discovered from the use of the prototypes. Other data was also collected for analysis, including six graphical organisational process descriptions and documentation material such as videos, reports and personas. Table 2 summarizes the data.

2.2 Analysing data

The analysis of the data comprised three parts: within case analysis, cross case analysis and theory based analysis. Within case analysis began with detailed write-ups consisting of transcripts of the recorded interviews and more mind mapping summaries (43 pages of transcripts), as well as going through the post-interview organisational documents.

Table 2 Overview of data sources

What	*Amount of data*	*Comment*
Company interaction		
Semi-structured interviews	10 with an average length of 74 min	Involving between 1 and 4 interviewees
Guided tours in the new product development department	7 with an average length of 24 min	Observing tools and documentation methods and placement
Documentation		
Transcripts of interviews	43 pages	Including a filled-out interview guide for each case
3 Design tools brought to 4 of the interviews	3 × 4 A3 sheets	Focussing on process of product development, tools used and theoretical purpose of prototype
Organisational descriptions of company and their NPD process	6 presentations	PPTs or graphical illustrations
Objects used in the development process		
Physical prototypes (All)	19 pc.	All mentioned and visualised
Video from Kickstarter (VAV)	3 min and 44 s	during the interviews
Video on products (AXT)	2 min and 50 s	Examples of working with prototypes
Personas (SBS)	15 examples	as video, personas and documentation
Evaluation sheet from tempo-process (PL)	(of 2 pages each)	of prototype usage
Video from co-creation workshop (EXP)	2 pages 4 min and 34 s	

The cross case analysis was conducted by focussing on 19 different prototypes used in the companies and comparing them in graphs of different trade offs (level of functionality, stakeholder involvement and type of requirement elicited). The prototypes were selected by the criteria of which the interviewees most spoke and to which they assigned the greatest value. In this way, we gained insights in the interviewees' perception of prototypes rather than us asking for specific types or purposes. As an example, the interviewees were not aware of the terminology of requirement elicitation or the concepts of *unknown unknowns*. Basically, we attempted to avoid any pre-assumptions transferred from the interviewer, but to gain an honest insight into how prototypes were understood in different companies in terms of semantics and application wise. This allowed us further to explore the cases in the context of literature and to identify similarities and differences relevant to further theoretical analysis. The evaluation of the 19 prototypes was conducted by the authors from directly extracted from the protocol, discussing and evaluation, theory comparison and comparing photos. The shaping of the new terminology, *prototrial* and *prototrial-driven* cultures, has been a continuous discussion among the authors and has evolved along with the analysis.

3 Analysis

Analysis consisted of clustering and evaluating the 19 identified prototypes used in different contexts of the companies. The aim was to clarify the usage and interactions of the prototypes. This was done by focussing on functionality and time in the development process, stakeholder involvement and requirement elicitation.

3.1 The 19 prototypes evaluated through level of functionality

The 19 prototypes were evaluated by level of functionality and the point in the design process when they were used (see Figure 1). The functionality bar went from lowest functionality mock-ups or sketches to high-functional prototypes testing a specific detail of a concept idea as part of a parallel exploring process. Inspired by Ulrich and Eppinger (2008) six-phase model, we found three phases suitable when placing our identified prototypes: 1. Concept development, 2. Detail design and 3. Testing and refinement.

Among the 19 prototypes, both Wizard-of-Oz prototypes and functional prototypes were identified. Looking more closely at the graph, four types were identified:

1. Low-functional prototypes in the concept development phase
2. High-functional prototypes in the concept development phase
3. Low-functional prototypes after the concept development phase
4. High-functional prototypes after the concept development phase.

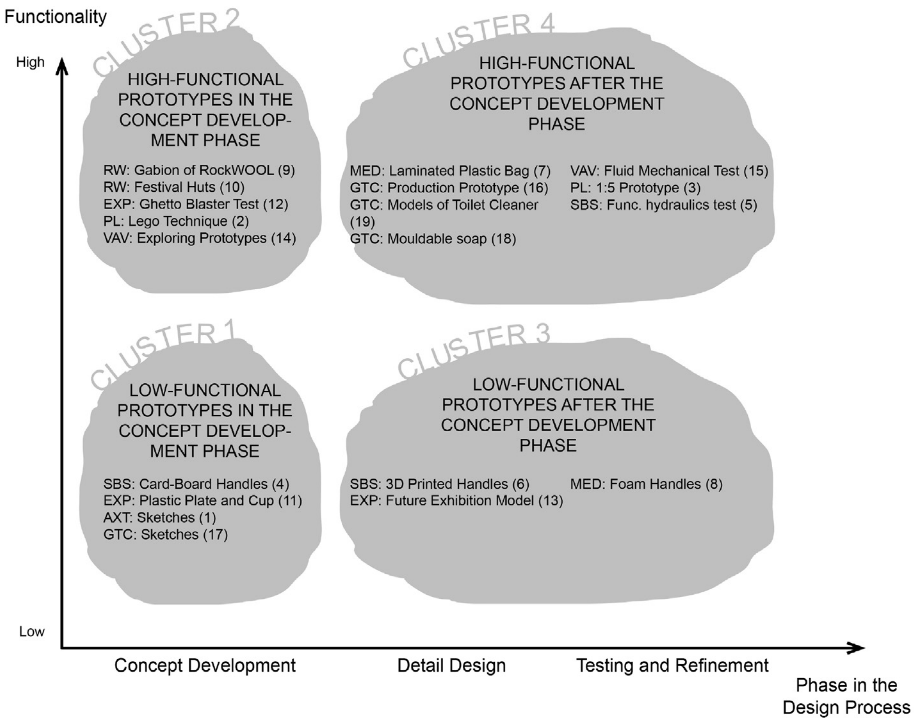

Figure 1 Prototypes evaluated on functionality and phase in the design process. The numbers indicate the number of prototype mentioned in Table 1

3.1.1 *Low-functional prototypes in the concept development phase*

Prototypes nos. 1, 4, 11, and 17 are in this category. These prototypes can be defined as the experience or low-fidelity prototypes described by (Buchenau & Suri, 2000; Hare et al., 2013). They are a classical part of a concept development phase since they are quick to use and allow a high degree of freedom. **Figure 2** presents two of the identified low-functional prototypes identified in this study. Scandinavian Business Seating used such prototypes in user-involving activities to articulate needs and insights from their extreme users (no. 4). The aim of these prototypes was to gain new ideas and especially help users articulate new unknown insights, thus helping to elicit *unknown unknowns* in the social expectations category stated by Sutcliffe and Sawyer (2013).

The toilet care company and Axtech used sketches to facilitate discussions of internal preferences and knowledge. Experimentarium used their low-functional prototype of a plastic plate and glass to communicate an idea, which later, was tested through prototype no. 12. In all three cases, the prototypes supported elicitation of *known knowns* or *unknown knowns* (Figure 2).

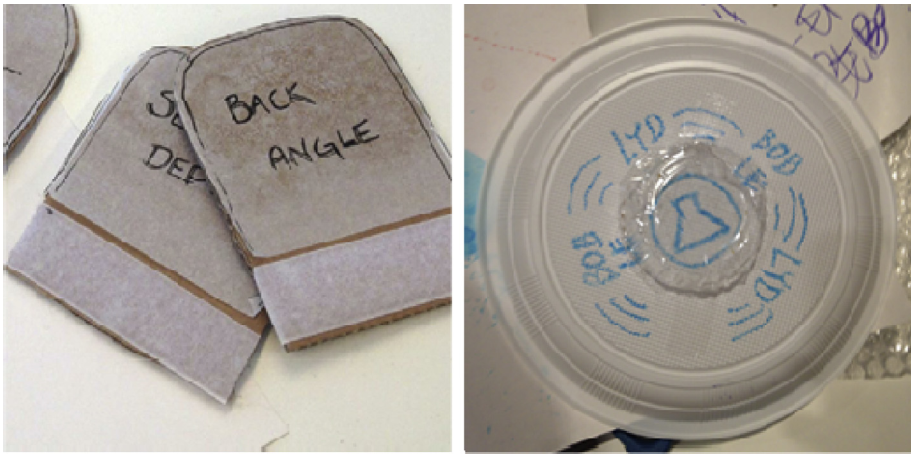

Figure 2 Example of low-functional prototypes used in the concept stage. From the left prototype handles of cardboard used by Scandinavian Business Seating (no. 4) followed by prototype no. 11, communicating the idea of a soap bubble being affected by the vibration of sound.

3.1.2 High-functional prototypes in the concept development phase

These are prototypes nos. 2, 9, 10, 12 and 14. They all had a high level of functionality and did not intend yet to target a final product or solution. The degree of freedom was high and the prototypes were all part of many parallel processes and not one product's development track. This approach covers an area where the strategy could be described as initially testing several different product ideas simultaneously, learning from these and then combining the learning to a new set of product requirements.

> *We actually built many different prototypes in the first session and then further developed one prototype including the most important findings from all the others*. Exhibition Developer, Experimentarium.

This method is cited as being supportive of managing complexity in a project (Dow et al., 2010; Snowden & Boone, 2007). By being highly functional and

Figure 3 Examples of high-functional prototypes in the concept stage. From the left Lego Technique prototypes used by PREZIOSO Linjebygg (prototype no. 2), huts for Roskilde Festival used by ROCKWOOL (prototype no. 10), testing soap bubble exhibition idea used at Experimentarium (prototype no. 12) and Vaavud exploring magnetism and the magnometer in an iPhone (prototype no. 14)

part of a parallel prototyping process, these kinds of prototypes allow companies to learn and elicit various *unknown unknowns* regarding market, new collaborating partners, social expectations, and the unintended consequences of new technologies or real-life physical contexts one fails to understand. These all fit Sutcliffe and Sawyer (2013) categories of *unknown unknowns*.

3.1.3 Low-functional prototypes after the concept development phase

Prototypes nos. 6, 8 and 13 are so-called communication prototypes (Blomkvist & Holmlid, 2011; Lim et al., 2008), seeking to communicate an idea rather than test a concept (Figure 4). In the dialogue with other stakeholders, they helped articulate *known knowns* and *known unknowns*, thus, serving as tools in the further implementation process by creating alignment among different stakeholders (Holford et al., 2008) (Figure 4).

3.1.4 High-functional prototypes after the concept development phase

Prototypes no. 3, 5, 7, 15, 16, 18 and 19 are defined as having high levels of functionality while being used in the later stages of the design process. Two examples can be seen in Figure 5. Their role was identified as exploring shapes and versions of a well-understood product, helping the companies define known unknowns, and mechanical-related *unknown unknowns*. As a result, they are described in literature as proof-of-product prototypes (Ulrich & Eppinger, 2008; Yang, 2005) (Figure 5).

3.2 Who is interacting with the prototypes?

The prototypes were further mapped by type of stakeholder involvement and connection to elicited requirements. They were clustered in groups

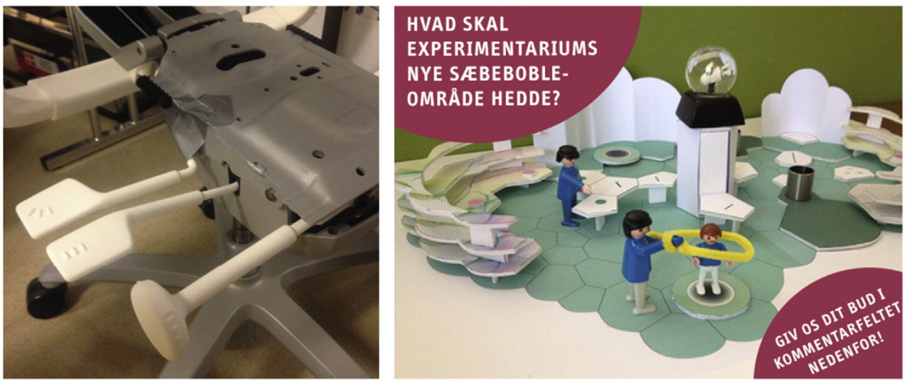

Figure 4 Example of a low-functional prototype used in the stages after concept development. From the left 3D printed handles used by Scandinavian Business Seating (prototype no. 6) and a small scale model of the future soap bubble exhibition at Experimentarium (prototype no. 13)

Figure 5 Example of high-functional prototypes used in the stages after concept development. From the right, hydraulics test used by Scandinavian Business Seating (prototype no. 5) and Vaavud testing fluid mechanical properties in a wind simulator (prototype no. 15)

depending on whether they were used in one of the three contexts defined in the theoretical section:

1. Internal/Internal: Used in the internal conversation with stakeholders inside the development department
2. Internal/External: Used in the conversation with stakeholders outside the development department yet inside the company
3. External/External: Used in the conversation with stakeholders outside the company. Moreover, the types of requirement targeted during the usage were noted.

The findings are presented in Table 3, and are further described in the sections below.

3.2.1 Internal/internal interaction

Six of the 19 prototypes were used purely internally in the development department. The prototypes used in the concept development phase (nos. 1, 11, 14, and 17) were used to get an initial understanding of the problem space, thus helping to elicit *known knowns*, *unknown knowns* and *unknown unknowns*. In later stages, the internal prototypes were aiming at testing *known unknowns* as regards shape decisions (nos. 5 and 19) or mechanical challenges (no. 15).

3.2.2 Internal/external interaction

Seven prototypes were identified as interacting with stakeholders outside the development department while still employed in the company. A reason for including these stakeholders was to articulate unknown knowledge.

Other prototypes simply could not be made without the knowledge from other departments, (nos. 3 and 18). In these cases, the development department was

Table 3 Type of stakeholder interacting with the analysed prototypes combined with the targeted requirement

Prototype	*Type of stakeholders*	*Requirement target*
1. Used internal/internal		
Prototypes nos. 1, 5, 14, 15, 17, 19	Designers, engineers, People in the development team	Getting an initial problem understanding Decisions on shape and visual appearance Mechanical proof-of-concept tests
2. Used internal/external		
Prototypes nos. 3, 6, 8, 11, 12, 18	Service staff, marketing, explainers/guides, chemist, mechanical engineers, workers	Insights into the product seen in different internal use-contexts Solving technological challenges as regards areas not included in the development department (e.g. chemistry)
3. Used external/external		
Prototypes nos. 2, 4, 7, 9, 10, 13, 16	Festival goers, potential business partners (Plasmo), potential investors, visitors in the science museum, installers of product, salesmen of the product, extreme users, researchers	Insights into external use contexts including new user needs Knowledge on how to solve a problem Buy-in from external stakeholders *Unknown unknowns*

clearly aware of *known unknowns* in either chemical or mechanical fields and therefore involved other departments to clarify the issues.

3.2.3 External/external interaction

Six prototypes were identified and characterised as means for starting conversations with people outside the company. In the cases of Scandinavian Business Seating and ROCKWOOL, the prototypes were designed openly to enable exploratory discussions with users on topics from usability to use context, to achieve a holistic understanding of the product. ROCKWOOL has even built a user observatory and regularly invites construction workers to install their solutions. R&D department employees observe the workers and afterwards ask clarifying questions to understand the users' preferences.

> *When I asked my engineers what they are designing they would refer to thermal resistance and U-values. But when observing the German installers in our user-observatory to install our products, the engineers suddenly saw our products in a totally new use-context and identified problems not related to insulation-effect*. R&D Manager, ROCKWOOL.

PREZIOSO Linjebygg prioritised the inclusion of oilrig workers and academic experts in the development project. In this way, the external involvement helped articulate *unknown unknowns* about the holistic perspective of a product, while also serving as an internal tool to enlighten people about the importance of seeing the product in a broader perspective.

3.3 Requirement elicitation

Having mapped the prototypes in terms of functionality and stakeholder involvement, we will now elaborate on findings when mapping how the 19 prototypes helped the companies discover *known knowns, unknown knowns, known unknowns* and *unknown unknowns* and identify observed approaches that encourage the elicitation of *unknown unknowns*.

3.3.1 Mapping the requirement performance of the prototypes

Since certain prototypes were identified as eliciting several types of requirements, the placements in Table 4 represent the most dominant requirements. However, Table 4 has been divided into nine areas rather than four to ensure that the complexity of type of requirement elicitation is indicated. The grey area and bold font highlights the prototypes that especially helped companies to identify *unknown unknowns*.

We found that the companies do not limit prototype usage to only one particular requirement area. For example, the start-up company Vaavud was given

Table 4 Prototypes clustered in relation to requirement elicitation outcome. The letters indicate the design phase: (C) = concept development, (D) = design detail, (T) = testing & refinement and the numbers refers to the numbering of prototype in Table 1

	The detail of the requirements are known to the development team	*The detail of the requirements are to a certain degree unknown to the development team*	*The detail of the requirements are unknown to the development team*
The presence of the requirements is known to the development team	AXT: sketches (C) (1)	SBS: 3D printed handles (T) (5) MED: foam handles (D) (8) GTC: sketches (C) (17)	VAV: fluid mech. test (T) (15) GTC: mouldable soap (D) (18)
The presence of the requirements is to a certain degree unknown to the development team		SBS: func. hydraulics test (D) (5) MED: laminated plastic bag (D) (7) EXP: future exhibition model (D) (13) GTC: models of toilet cleaner (D) (19)	**PL: 1:5 prototype (T) (3)** **EXP: BoomBlaster test (C) (12)** **GTC: production prototype (D) (16)**
The presence of the requirements is unknown to the development team		**PL: lego technique (C) (2)** **RW: gabion of RW material (C) (9)**	**SBS: cardboard handles (C) (4)** **RW: festival huts (C) (10)** **EXP: plast plate and cup (C) (11)** **VAV: exploring prototypes (C) (14)**

an extremely explorative challenge in a university-based student course: *How to utilise the sensors of a smartphone in extreme sports?* To answer this, they created several prototypes (no. 14), which explored the *unknown unknowns* of this challenge's solution space in functional ways. However, when the final idea and concept about a mobile wind measurement function was decided, the prototypes (no. 15) changed to a more evaluating character testing details considered as *known unknowns*.

This development is natural as product understanding increases. One could therefore expect that *unknown unknowns* would only be identified in the early stages of product development. However, the letters in parentheses in Table 4 illustrate that the requirement of *unknown unknowns* was not restricted to the concept development phase (C) of the product development, but also appeared in later stages (*Design Detail (D)* and *Testing and Refinement (T)*).

Hence, the type of requirement elicited was not limited to one specific part of the product development process.

3.3.2 Approaches encouraging the elicitation of unknown unknowns

Since Sutcliffe and Sawyer (2013) stress the importance of eliciting *unknown unknowns* in engineering design projects, we were particularly interested in examining what factors seemed to encourage their identification. Sutcliffe and Sawyer (2013) state that *a first step to a resolution of the problem is recognising that there may be missing knowledge, and being prepared to invest resources in finding out if there is, and if so, where the gap lies*. Moreover, Ramasesh and Browning (2014) suggest that the framing of the question highly reveal the intent and potential to elicit *unknown unknowns*. Hence, we clustered the prototypes according to the degree of freedom and openness towards *unknown unknowns* (Table 5).

3.3.3 Design task with low degree of freedom

Eight prototypes were categorised as having a low degree of freedom, covering tasks only searching for incremental improvements. In this context, prototypes were used to represent an already existing idea and to get feedback from relevant stakeholders. In this case study, companies involved with traditional product design processes often used this method, though the strategy differed from company to company. Even though presenting their old products with certain modifications for users, the approach of Scandinavian Business Seating was very open and exploratory, including the so-called 'out-of-the-box questions' (Ramasesh & Browning, 2014). They were seeking to learn something unknown.

Table 5 The prototypes mapped by degree of freedom in the solution space and contextual attitude towards *unknown unknowns*. The letters indicate the design phase: (C) = concept development, (D) = design detail, (T) = testing & refinement. The numbers refer to prototype number in Table 1. The prototypes written in bold were identified to help the companies to elicit unknown unknowns

	Design task with low degree of freedom	*Design task with medium degree of freedom*	*Design task with high degree of freedom*
Neglect the existence of *unknown unknowns*	SBS: 3D printed handles (T) (6) MED: foam handles (D) (8) VAV: fluid mech. test (T) (15) GTC: models of toilet cleaner (D)	AXT: sketches (C) (1) GTC: sketches (C) (17)	
Recognise the existence of *unknown unknowns*	**PL: 1:5 prototype (T) (3)** SBS: func. hydraulics text (D) (5) EXP: future exhibition model (D) (13) GTC: mouldable soap (D) (18)	**PL: lego technique (C) (2)** **SBS: cardboard handles (C) (4)** MED: laminated plastic bag (D) (7) **EXP: plastic plate and cup (C) (11)** **EXP: BoomBlaster test (C) (12)** **GTC: production prototype (D) (16)**	**RW: gabion of RW material (C) (9)** **RW: festival huts (C) (10)** **VAV: exploring prototypes (C) (14)**

In one project we just gave some of the most well respected Norwegian architects one of our chairs and said: Go ahead; shoot us down. Manager of the Product Development Department at Scandinavian Business Seating.

In comparison, designers at the German toilet care company were more evaluative, with several internal iterations of a prototype's physical shape and fragrance. They used the user-involving part as confirmation of their hypothesis of a good product. Their approach was therefore confirming known unknowns rather than discovering completely new unknown aspects of their product.

3.3.4 Design task with medium degree of freedom

Eight prototypes were categorised as having a medium degree of freedom, aimed at solving well-defined challenges with a relatively defined final solution. Customer requisitions for Axtech and PREZIOSO Linjebygg, for example, serve as an example of an initial task that provides the context and understanding of the problem.

Again, we observed a difference in how companies approached the task, which affected prototype usage. In the design process of PREZIOSO Linjebygg, participants were forced to come up with several different physical prototypes to solve the same problem. They also included many different stakeholders to view the problem from different angles. This is interpreted as an example of conscious targeting of *unknown unknowns*. At Axtech however, employees were gathered in meeting rooms and defined different solutions to the problem. The prototypes used were simply sketches on paper. These would later be converted to digital formats in the form of CAD models. In this setting, the awareness and acceptance of *unknown unknowns* seemed lower.

Interestingly, The toilet care company was targeting *unknown unknowns* more in the production method development than in the development process of the actual product. An interviewee made this observation:

> *We had never made mass-produced soaps in round shapes before. We didn't have a clue how to do it. Therefore, we went to food industries to investigate how they made gum, meatballs and even chocolate.'* Chemical design engineer at the German toilet care company.

This illustrates how the perceived known knowledge of a company and the acceptance of *unknown unknowns* affect the product development process.

3.3.5 Design task with high degree of freedom

Three prototypes were categorised as having a high degree of freedom. Here, the overall aim was to explore completely new product ideas in parallel prototyping processes. This was observed at ROCKWOOL who has a library of challenges from employees worldwide. The scopes of the challenges cover everything from production issues to end-use situations or even the frustrations of individual employees. R&D employees are free to test solutions to stated challenges in highly exploratory ways that might or might not lead to new business or product ideas.

> *As an example, one of the employees was building a new carport at home. He thought about how he could get rid of the water in front of the carport in case of heavy rain. In this process, he built a prototype out of ROCKWOOL's existing products, which, unlike rock wool insulation that repels water, absorbs water. He placed the material in a gabion and then showed it to his manager in the R&D department*. R&D Manager ROCKWOOL.

The employee's idea has now resulted in collaboration with the gutter company Plasmo, which has tailored their concept to the specially designed material from ROCKWOOL.

A final observation is that none of the three prototypes match the category of neglecting *unknown unknowns* in a highly free solution space. This is understandable, since allowing a highly free solution space works conjointly with a conscious targeting of *unknown unknowns*.

4 Results

Our work's first contribution is the mapping of different real-life utilisations of prototypes in contemporary engineering design projects covering a broad span of applications. We identified four different types of prototypes by level of functionality:

1. Low-functional prototypes in the concept development phase
2. High-functional prototypes in the concept development phase
3. Low-functional prototypes after the concept development phase
4. High-functional prototypes after the concept development phase

As expected, the prototype usage depended on when they were used in the design process. Types 3 and 4 were used either to test for *known unknowns* as regards the implementation and realisation of the product or securing alignment for supporting the future process by eliciting *known knowns* and *known unknowns*.

Regarding elicitation of *unknown unknowns,* we saw that Types 1 and 2 performed in this area. Sutcliffe and Sawyer (2013) define *unknown unknowns* to cover the areas of fast-changing markets, fashion dependent products, social expectations, and the unintended consequences of new technologies or real-life physical contexts one failed to understand. Here, we saw that the low functional prototypes in the early stages of the product development process only supported the companies eliciting *unknown unknowns* about user needs and preferences, whereas high functional prototypes in the early stages of the design process supported the companies identifying *unknown unknowns* in wider aspects of the palette described by Sutcliffe and Sawyer (2013). By being part of parallel prototyping development processes, these functional prototypes worked more as experiments testing different hypotheses rather than being iterations in one linear development process.

The second contribution is the finding that a broad span of usage areas also was observed in the contexts of stakeholders interacting with the prototypes. These were as follows: 1. *Internal/Internal*, 2. *External/Internal* and 3. *External/External*. It appears *External/External* had the highest potential in defining *unknown unknowns* as regards user preference and holistic understanding of a product. *Unknown unknowns* concerning more mechanical properties and contexts were not observed to be in particular need of *External/External* stakeholder involvement. Here, building prototypes *Internal/Internal* or *Internal/External* of the product development department were useful to articulate valuable *unknown unknowns*.

The third and final finding is that prototypes helped the companies elicit requirements in all the fields of *known knowns*, *unknown knowns*, *known unknowns* and *unknown unknowns*. Contradicting Sutcliffe and Sawyer (2013) statement about the limited potential of prototypes to elicit the most valuable type of requirement, *unknown unknowns,* we saw that several prototypes supported the companies in this elicitation, and this ability and potential neither depended on the point in time in the development process nor the degree of freedom the engineer was given in a certain design task. Instead, the potential of the prototype was reached depending on the attitude towards the existence of *unknown unknowns* in the respective companies. Even in challenges with low degrees of freedom regarding the solution space, the attitude towards *unknown unknowns* was determining the prototypes' ability to identify the rare, but important, requirement type. Finally, we observed that prototypes used in challenges with a high degree of freedom regarding the final solution only helped elicit *unknown unknowns*. Hence, we conclude that the potential for identifying *unknown unknowns* with a prototype lies in the companies' conscious targeting of *unknown unknowns* and to a certain degree in the degree of freedom of the solution space.

5 *Introducing prototrials and prototrial-driven cultures*

The findings of this study are limited to the eight cases covered; however the variety of cases and the decision to select 19 different prototypes provide a broad spectrum of prototype aspects. The broad range of applications suggests the term 'prototype' should be subdivided, as the current nomenclature seems to create misunderstandings, especially for prototypes used in the earlier stages of product development processes. For instance, we believe that the high-functional prototype described in section 3.1 is not covered by (Sutcliffe & Sawyer, 2013) definition. They seem to understand a prototype as evaluating iterations of an existing product idea in the later stages of product development, or Context 3 in Figure 1. Hence, they state the limited potentials of prototypes to identify *unknown unknowns*. This lack of definition is present in the general community, and we therefore introduce the term *prototrial and prototrialing*, covering these functional and simultaneously-produced prototypes, to fully grasp their role in new-product-development. As a noun, *prototrials* cover high-functional prototypes used in the concept development process, but with low fidelity compared with the final product. Per definition, these prototypes cannot be treated as stand-alone entities, as they are a part of a larger exploration process with the goal of identifying *unknown unknowns*. The verb *prototrialing* covers this overall activity of simultaneous experiments and tests essential for these prototypes; it is an active trial to learn and understand the solution space rather than only alternative solutions for one already defined function or solution. In this way, they differ from works-like prototype presented by Koo et al. (2014) and Ulrich and Eppinger (2008) since works-like prototypes seek solutions for one specific product idea, whereas *prototrials* are more exploratory by nature and investigate what the final product should be. Hence, *prototrials* and *prototrialing*, are divergent and concept generating rather than convergent and confirmatory. An example of *prototrials* and *prototrialing* in this case study is the prototypes built by Vaavud used to come up with a future product for extreme sports in the beginning of their project. Another example is how ROCKWOOL had their entire department working on several different product ideas while not knowing which one in the end would be implemented in the end. The value of *prototrials* is that they consciously target *unknown unknowns* in more aspects defined by Sutcliffe and Sawyer (2013) instead of only human-centred *unknown unknowns*, therefore becoming relevant in all industries within business-to-business and industrial companies, where the challenge does not only concern private consumers. We are not undermining the value of low functional prototypes in conceptual development phases, but simply arguing that *prototrial*s will help product developers learn broader aspects of the *unknown unknowns* faster and more effectively. Figure 6 illustrates where *prototrials* are placed compared with other utilisations of prototypes.

As mentioned earlier, we observed how the attitude towards the existence of *unknown unknowns* highly influenced the prototypes' ability to identify *unknown unknowns*. This attitude was not only defined by the use of exploratory prototypes, but also initiated and supported by other characteristics, such as the physical working space, new documentation processes, new roles inside

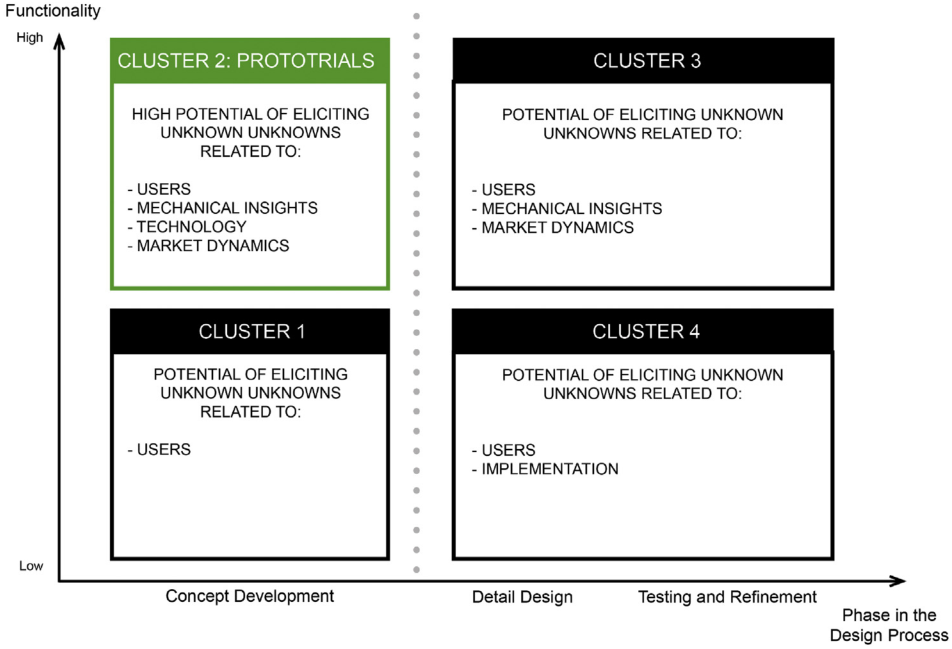

Figure 6 Illustration of where prototrials *perform in terms of requirement elicitation, functionality and time in the development process*

the development department, challenge formulation and framing, and resources. Hence, we will expand the understanding of a *prototrial* and define it as *the physical statement of a company culture consciously targeting unknown unknowns,* and will define these cultures as *prototrial-driven cultures*.

With this expansion, we wish to stress that the value of a *prototrial* and *prototrialing* is not observed as a design method in itself, but in the culture of which it is a part. It is a culture that strategically puts *unknown unknowns* into play to make novel products with great market potential, not only focussing on human-centred design and the corresponding *unknown unknowns* of people, but also targeting all aspects of *unknown unknowns*.

The companies in this case study that have successfully incorporated this mind-set spent several years in the change process and depended on managers continuously leading the way of change. This indicates that a company aiming at becoming more *prototrial-driven* must be willing to invest not only in new tools but also in new organisational structures.

6 Findings from specific companies

In the following section, we provide the reader with some specific insights observed in the companies that were particularly adept at creating and using simultaneous, high-functional prototypes – which we denote as *prototrial-driven* behaviour, in the early stages of new product development. Though case specific, the insights should inspire researchers or managers of early-stage product development to implement more exploring and *prototrial-driven* cultures.

6.1 Physical space supporting prototrials

The *prototrial-driven* culture was represented through the physical space of the companies. Medicologic had installed a workshop with tools as 3D-printers and drills among others in the middle of their open office space.

In a similar way, ROCKWOOL had made physical changes and enabled easy access to building and prototyping tools and user observatories. PREZIOSO Linjebygg had implemented a tool area in their meeting rooms to support people materialising their ideas and concepts.

The short distance to building shops outside the company was also mentioned as of high importance. Ordering online was simply too slow and hampered the momentum of a building project. Supported by the growing field of ergonomic psychology (Vischer, 2008), we propose further research to investigate how the physical interior affects the prototyping behaviour.

6.2 Getting the challenge right

An interesting factor, which was observed to influence the *prototrial-driven* culture, was the formulation of the challenge the R&D workers had to solve. ROCKWOOL defined challenges by their challenge library. At PREZIOSO Linjebygg and Medicologic, the challenges formed by customers were redefined to include a more exploring nature. The head of R&D at ROCKWOOL mentioned the term 'playful co-workers' as a goal in their product development department. But what is playful? In this case, *playful* was interpreted as curious, alternative thinking, and exploring. Supported by our own initial studies, we suggest the formulation of the task to trigger a more exploring approach to a problem eventually leading to the building of *prototrials* (Jensen, Birkeland, & Steinert, 2016).

6.3 Thinking documentation differently

ROCKWOOL's and PREZIOSO Linjebygg's implementation of a *prototrial-driven* culture affected the learning processes of the companies. This required a reconsideration of the existing documentation processes. Since the main intended requirement elicitation in both approaches of the companies were *unknown unknowns,* the existing documentation process failed at incorporating this inherent unpredictability by documenting backward rather than forward.

ROCKWOOL, hence, changed their documentation from being solely 20 page long reports to be driven by functional prototypes combined with five pages long written descriptions. They now focus on future tasks rather than checking whether all predefined tasks in an organisational process description or gate has been conducted.

> *We now focus on what needs to be done and not what has been done, which is a huge difference for us*, R&D Manager, ROCKWOOL.

Erichsen, Pedersen, Steinert, and Welo (2016) investigate this phenomenon and argues that one of the cores values of a prototype built in the early stages of engineering design is to bring tacit knowledge further in development processes.

6.4 New types of project managers

In ROCKWOOL, employing the strategy of changing the development process towards more *prototrial-driven* activities, they found that new types of project managers were required. The *prototrial-driven* processes were propelled by the motivation of the employees, and thereby, gave rise to a huge sense of freedom to the employees. However, in this context, a risk was identified in that employees failed to see their role in a project or department and thereby became demotivated. To run a motivational-driven development culture ROCKWOOL therefore prioritised two kinds of managers.

The full-speed-a-head manager: A person with a background in innovation process and facilitation of innovation who sets no limits, has high expectations, and pushes the employees to work in a certain direction.

The motivational people-person: The motivating people-person that helps and supports employees to remember their competencies and helps them define their role in the department and different projects.

We find this observation particularly interesting since it calls for studies and insights on the skills required to be a coach or facilitator of teams in the early stages of product development. This claim is supported by Goldschmidt, Casakin, Avidan, and Ronen (2014) and recently addressed by Adams, Forin, Chua, and Radcliffe (2016) both arguing that one of the tasks as a coach in innovation processes is helping people *to make sense of it all*.

7 Conclusion

In this study, we answer the research question stated by Elverum and Welo (2014): How do companies utilise prototypes? Our multi-case study of eight companies and 19 prototypes provides the community with a gallery of prototype applications in industry. Moreover, inspired by Tracey and Hutchinson (2016) and their focus on uncertainty in the design process, we mapped the prototypes' ability to elicit requirements in terms of *known knowns*, *known unknowns*, *unknown knowns,* and *unknown unknowns* (Sutcliffe & Sawyer, 2013), looking in particular for prototypes eliciting *unknown unknowns,* as Sutcliffe and Sawyer (2013) actually state that prototypes have a limited potential in identifying them.

The results show that prototypes were used in a broad spectrum of utilisations in several parts of the design process and supported the uncovering of *unknown unknowns*. The high-functional prototypes used in the concept development part of the engineering design process were observed to be particularly powerful. These prototypes were found to effectively target *unknown unknowns* in more of the aspects defined by Sutcliffe and Sawyer (2013) than only human-centred *unknown unknowns*. Hence, they become relevant in business-to-business or more industrial companies, where the challenge does not only concern private consumers. We, thus, contradict Sutcliffe and Sawyer (2013), concluding that prototypes can indeed help companies identify *unknown unknown*s, although we believe their reasoning can be explained by the also observed wide usage of prototypes, which leads to broader or narrower definitions of the term 'prototype'. Sutcliffe and Sawyer (2013) understand prototypes simply as tools to evaluate ideas, and used in the later stages of the engineering design process.

To avoid this misunderstanding and support the application of functional prototypes in the early stages of the engineering design process, we introduce the new terms *prototrial* and *prototrialing*. These terms seek to cover the parallel experimenting and testing nature essential for these prototypes used in the concept development process of an engineering design process.

We also established that the companies' attitudes towards the existence of *unknown unknowns* highly influenced the ability of the prototype to elicit them. Hence, we expand the understanding of a *prototrial* and define it as *the physical statement of a company culture consciously targeting unknown unknowns* and name these cultures *prototrial-driven cultures*. The value of a *prototrial* and *prototrialing* is not observed as a design method in itself, but in the culture of which it is part. This culture strategically puts *unknown unknowns* into play and focuses on more categories of *unknown unknowns* than the purely user related.

By introducing the idea of *prototrials* and *prototrial-driven* cultures, we hope to inspire companies as well as engineers to develop more explorative and testing orientated organisational structures. It is our firm belief that such approaches will lead to the most radical innovations of the future.

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Appendix I. Presentation of the eight companies

The 'hard-core engineering' Company: Axtech

The Norwegian company Axtech (AX) designs and builds lifting mechanisms used offshore capable of lifting weights from 20 to 100 tonnes. The sizes of its solutions are extreme – up to half the size of a soccer field. Because of these sizes, Axtech does not build physical prototypes of its products. Instead, calculations, simulations and CAD drawings are used throughout the project and serve as decision-making facts.

PREZIOSO Linjebygg

PREZIOSO Linjebygg (PL) provides services and products to the oil and gas industry, both offshore and onshore. Inspired by innovation processes derived from IDEO and Stanford University, it introduced its own development process, Tempo Process, in 2010. This process includes several prototyping sessions. PL even implemented physical changes in the meeting rooms by installing smaller workshop areas with basic prototyping tools.

The classical design company: Scandinavian business seating

Scandinavian Business Seating (SBS) is a 100-year old company producing chairs for office environments, etc. As traditional product designers, prototyping is in their genes. At SBS, this also means involving many stakeholders in the prototypes, e.g. bringing an old chair to some of their extreme users and having them give feedback and ideas for further improvement.

The start-up company: Vaavud

Vaavud (VAV) is a Danish start-up founded in 2012. Its product is a small, mobile wind-meter utilizing a smartphone accelerometer. This was a result of a six-month-long explorative master course at the Technical University of Denmark. The initial challenge was: *How can we utilize the sensors of a smartphone for new applications in the area of sport?* With a successful Kickstarter campaign, the product was launched in summer 2013.

The science museum: Experimentarium

The Danish science museum Experimentarium (EXP) includes 200 employees and has 300 000 visitors annually. We learned about its use of exploring co-created prototypes for a future soap bubble exhibition. This process included several workshops where participants had to create prototypes in the exhibition hall, allowing them to interact and test with museum visitors.

The consultancy: Medicologic

Medicologic (MED) is a Danish design consultancy helping people realize potential ideas in the medical field, either for production or further funding opportunities. MED helps in defining requirements and building prototypes for customers with promising ideas. MED builds several prototypes in their internal workshop in this process.

The insulation company: ROCKWOOL

The Danish company ROCKWOOL (RW) develops and produces insulation material for the entrepreneurial industry. The organisation of the R&D department was changed in 2008 to favour the complex processes of creativity and innovation, inspired by Ralph Stacey's theories on Complex Responsive Processes and managing the unknowable. With this organizational change, prototypes became a core part of the documentation process and 10% of the R&D budget is assigned to non-project-specific prototypes.

The toilet-care designers

The toilet care company is a German family business in the toilet-care industry. Their business is driven by direct market demand and the fact that consumers in this field *'just want to try out new stuff'*. In order to align product with mass-production methods, the product development team involve production-methods very early in the new product development process, prototyping the actual product and the production methods in parallel.

Appendix II. Explanation of prototypes

No.	*Prototype title*	*Description*
1.	CAD drawings and sketches	Axtech met internally and sketched different suggested solution of a given challenge. They knew the requirement and task to solve with the product and hence gathered their internal experts to identify the solution.
2.	Smaller models of Lego, wood and cardboard	PREZIOSO Linjebygg used Lego technique in their tempo process. Through physical prototypes and strategic gathering of people the prototype support the articulation of unknown knowledge about the problem. While building the prototypes unknown unknowns about the problem were articulated as well.
3.	Scaled functional 1:5 or 1:10 prototypes	Later in the design process PREZIOSO Linjebygg would built bigger prototypes at their prototyping facilities in Trondheim. These are built in steel and resemble the final product.
4.	Cardboard add-on handles to existing office chairs	When involving the users Scandinavian Business Seating would include handles made out of cardboard to discuss placement of handles or even new functions.
5.	Functional hydraulics test	In the later stages in the design process Scandinavian Business Seating would built hydraulics for the chair to test if it worked as intended.
6.	3D printed handles	To evaluate the shapes and placement of handles of the office chairs Scandinavian Business Seating had several handles 3D-printed.
7.	A prototype made from a plastic bag and a laminating machine	Medicologic built this prototype for a nurse who had a new idea for designing plastic bags for medical purposes. She needed a convincing prototype to bring to potential investors.
8.	Foam models exploring shapes	Medicologic built these prototypes in foam exploring the shape of a medical device. Over 30 different shapes were evaluated.
9.	Water absorbing gabion	This prototype was build by an employee at ROCKWOOL who got the idea while building a new garage at home.
10.	Huts for Roskilde Festival	ROCKWOOL created very explorative festival huts as prototypes on Roskilde Festival. The company did not know where the project would end but observed stakeholders or interested people interacting with the prototype. This later helped identify new market possibilities.
11.	First prototype made of plastic plate and plastic glass	This prototype was made in the first round of a prototyping session during a co-creation workshop at Experimentarium. It was made to illustrate an idea about and exhibition applying and visualizing sound waves to bubbles.
12.	Testing set-up with a BoomBlaster	This prototype was built at Experimentarium to explore the experience and effect from prototype no. 11. It was built by covering a BoomBlaster with plastic. Further deep sounds were played while bubbles were put on the plastic. It was now investigated whether the bubbles vibrated as expected.
13.	Model of the future soap bubble exhibition	This model was built by Experimentarium to support communication processes on the new Bubble Exhibition when discussing topics from the final design to the name of the exhibition.
14.	Prototypes in the exploring phase. cardboard, sketches	These prototypes were built in the exploration of the solution space of the challenge given to the student team, which later turned into the start-up Vaavud. The picture in Figure 3 shows how the group tested how rotating magnets can affect the accelerometer in a smart-phone.
15.	Fluid mechanic test with 3D printed prototypes	These prototypes were built by Vaavud and brought to a wind simulator at the Technical University of Denmark to evaluate the fluid mechanical properties and accuracy of the proposed shapes.

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(*continued*)

No.	Prototype title	Description
16.	Prototyping production methods on smaller scale	At the toilet care company they had a whole department focussing and testing whether a certain product idea could be produced in mass-production scale. This means building up machines to produce products in appropriate quantity and quality.
17.	Prototyping shape through sketches	Drawn in the early stages of product development these sketches were used as ideations on the shape of the toilet cleaner at the German toilet care company.
18.	Prototyping power balls in mouldable soap	The prototype was used to test the physical stability and usability of the soap mixture of a toilet cleaner. The toilet care company had an idea of round-shaped soap/balls, but were lacking knowledge on production aspects of this idea. Hence they made a small test of the soap mixture by shaping soap balls by hand.
19.	Plastic models of toilet cleaners	These prototypes were built to evaluate the shape of the toilet cleaner meant to be hung inside of the water closet.

Appendix III. Interview guide

Theme: Introduction

Main question	*Additional*
Please, introduce yourself and your role in this company/your department	
How do a product development process normally take place in your company? From an initial idea to the final launch?	
How long did it take?	
Who has been involved in the product development process?	Mention all stakeholders and their roles. How did they come into play with the methods and events you just mentioned.
Which constrains did the development of the product have?	How did it affect the process? Did you actively use them in the development process?
How do you document the process?	

Output: a chronological timeline of the process including stakeholders, activities (including prototypes) and important roles.

Theme: Process of using prototypes

Main question	*Additional*
Why did you use prototypes?	What do you get from using prototypes
How many iterations or ideas did you consider before choosing the final technology?	
Do you use prototyping actively or only physical prototypes	Please explain both cases
In which phases of the development did you most often use prototypes?	Can you describe a typical process of using the prototype?
Who made the prototypes?	What material were they made from?
What is the level of detail on your prototypes?	
How do you evaluate the use of the prototype?	How do you take the learnings further?

Theme: Materials and method

Main question	*Additional*
Which methods do you use to make you prototype What are the main advantages with the different methods? How many persons do normally interact with the prototype at a time? Can you use the prototype more than ones? Have anything kept you from creating a prototype a new iteration? How much money have you spend on prototypes?	Materials

Theme: Output from the usage of the prototype

Main question	*Additional*
What was the out-put of the different prototype? How do you evaluate the usage of the prototype? Can you use the prototype more than ones? How does the prototype support the creative exploring process? How does a prototype support an evaluating process? How does a prototype support a communicating process?	

Output: a map of prototypes mapped on the circles of exploring, evaluating or communicating.

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