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On the use of directional and incremental prototyping in the development of high novelty products: Two case studies in the automotive industry

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ABSTRACT

Physical prototypes have always been important in engineering design. However, little is known about the role that prototypes play in the development of complex physical products. This paper investigates the role of prototypes and prototyping in the development of two novel product innovations recently launched by an automotive original equipment manufacturer (OEM). Through an exploratory case study, prototypes are found to provide the capability to aid learning and communication both within the development teams and across the organization. Actual prototype usage was found to encompass activities beyond merely the verification and validation purposes covered in traditional engineering design literature.

1. Introduction

In the search for improved innovation outcomes, new product development (NPD) has become an important field of research during the past several decades. Factors such as increased global presence and fierce competition combined with increased product complexity and shorter product life cycles have increased the pressure on streamlining the development process. Advances in computer systems have provided new opportunities for aiding the NPD process. Software tools such as computer-aided design (CAD), computer-aided manufacturing (CAM), product lifecycle management (PLM) systems and digital mockup (DMU) all promise increased NPD process productivity. However, there is no evidence that digital tools alone can fully replace physical models, especially when seeking differentiation through high novelty products where thinking outside-the-box and exploring the unknowns through experimentation are prerequisites for success (Martin, 2009; Quinn, 1985; Schrage, 2000; Thomke, 1998; Tidd and Bodley, 2002; Veryzer, 1998).

Prototyping—i.e., the activity of creating prototypes—has long been considered important in human-computer interaction (HCI) and software development (Lim et al., 2008). In this context prototypes play an important integral role in the overall development process. Agile software development, for example, is fundamentally based on an iterative and incremental development approach through the creation of a series of prototypes (Martin, 2002; Poppendieck and Poppendieck, 2003). Physical products on the other hand, especially complex product systems, are typically more demanding and time-consuming to prototype (Dahan and Hauser, 2002; Ullman, 2010; Ulrich and Eppinger, 2012). Since

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knowledge elicitation from prototyping is no less important for physical products, however, research efforts are needed to increase our understanding of the roles of prototypes and prototyping in this context. More specifically, this calls for a more comprehensive research-based understanding of prototyping in order to enable designers and engineers to more efficiently and effectively create high novelty products, as pointed out by Lim et al. (2008): "*Without conscious awareness of how prototypes influence the way users may interpret them during testing or how designers use them to identify problems, define designs, and generate more ideas, the results of using prototypes can lead to undesirable effects.*"

Product development models considered state-of-the-art within engineering design, such as the ones proposed by Pahl and Beitz (2007), Ullman (2010) and Ulrich and Eppinger (2012), do not rely extensively on prototyping during the early phases of the development process. Yet Ullman (2010) acknowledges the importance of prototyping in software development, raising the question as to whether a prototype-driven spiral model approach as the one proposed by Boehm (1988) could make sense in hardware development as well, especially when considering recent advances in rapid prototyping technologies. Furthermore, several new product development and innovation studies have found prototypes to be important in the early development phases (Bacon et al., 1994; Khurana and Rosenthal, 1998; Seidel, 2007; Tidd and Bodley, 2002; Veryzer, 1998). However, this body of research does not go beyond merely stating that prototypes are important in the early phases. Thus, there is a lack of insights on *how* prototypes are utilized and *why* prototypes are important in the early stages of the development process—beyond the obvious verification and validation purposes they serve. We therefore seek to gain further understanding on this topic by conducting exploratory case studies of recent product innovations. More precisely, we seek to investigate whether prototyping beyond validation and verification purposes takes place. If so, why are these prototypes created, what purposes do they serve and what prototyping strategies are employed by the development teams? Finally, we aim to identify the prototyping strategies used and to categorize and describe the types of prototyping activities that take place during the development process.

To begin bridging this research gap, we have conducted two in-depth industrial case studies. We selected to study the history of two significant product innovations that have recently been launched in the marketplace by a major automotive OEM company. The automotive sector was specifically chosen to continue to build on our prior work, where we found prototypes to be important tools in early concept development (Elverum et al., 2014). Furthermore, the automotive industry is a mature industry that produces technically complex products and product systems for high-volume applications, which is a context relatively unexplored within this research field. For one of the products, the history involved a thirteen-year period of development efforts. Semi-structured interviews and graphic elicitation with various stakeholders in the organization were used as the two main research methods. Physical artifacts and project documentation were also used as sources to increase the validity of the results.

The main contribution of this work is providing the research community and the industry with in-depth insights into how research and development teams can utilize prototypes and prototyping in the particular context of the study.

This paper is structured as follows: Section 2 deals with the theoretical foundation. Here we delve into the theory of prototypes and prototyping by discussing the current state-of-the-art and identifying research gaps. To complement the theory, we turn to other research fields such as HCI and software development where prototype-specific research has been an important topic for several decades. Section 3 describes the company background and the research methods in detail. Section 4 presents the overall findings while Section 5 discusses the findings in relation to existing theory and outlines an explanatory prototyping model. Concluding remarks, limitations of the study and suggestions for future work are given in Section 6.

2. Theoretical background

2.1. What is a prototype and what is prototyping?

According to Oxford Dictionaries, a prototype is "*A first or preliminary version of a device or vehicle from which other forms are developed.*" (Prototype, 2013). In the context of new product development and software development, a number of definitions do exist and these definitions differ mainly as to whether non-physical models are regarded as prototypes or not.

Ulrich and Eppinger (2012, p. 291) define a prototype as "*An approximation of the product along one or more dimensions of interest.*" Thus, their definition encompasses both non-physical and physical models and includes sketches, mathematical models, simulations, test components, and fully functional preproduction versions of the product. At the other end of the spectrum there exist more firm definitions that exclusively consider tangible artifacts, e.g., "*We define a prototype as a concrete representation of part or all of an interactive system. A prototype is a tangible artifact, not an abstract description that requires interpretation*" (Beaudouin-Lafon and Mackay, 2003, p. 122). Prototyping is naturally the *activity* or *process* of creating prototypes, as defined by Ulrich and Eppinger (2012, p. 291): "*Prototyping is the process of developing such an approximation of the product.*"

In this paper, we consider both physical and non-physical approximations to be prototypes. However, our main emphasis lies on physical prototypes. To avoid any potential confusion related to interpretations, we will clearly distinguish between physical and non-physical prototypes in the following.

2.1.1. Characteristics of prototypes

Although there are several frameworks that attempt to describe the different characteristics of prototypes, e.g., Lim et al. (2008), Michaelraj (2009), Ulrich and Eppinger (2012), no universally accepted framework exists. There are however a few common characteristics which are considered by most researchers. For example, resolution or fidelity are terms that are used to describe the levels of details represented in a prototype, often describing how close the prototype resembles (select functions of) the final product. Most researchers use these terms interchangeably, but McCurdy et al. (2006) use fidelity to describe the level of richness of the data and functionality of the prototype. Resolution, on the other hand, refers to the look and feel of the prototype.

In the relatively simple framework proposed by Ulrich and Eppinger (2012), prototypes are classified along two dimensions: *analytical* vs. *physical* and *focused* vs. *comprehensive*. Here a focused prototype implements few of the attributes of the final product, although it can be used for in-depth evaluation of various aspects or functions of the design. A comprehensive prototype implements most attributes of the product. A similar terminology is used by Beaudouin-Lafon and Mackay (2003) and Floyd (1984), using the terms *horizontal* and *vertical* prototypes. Here a horizontal prototype focuses on breadth, and in contrast to a comprehensive prototype, functions are not implemented in full detail but the prototype can be used for demonstration. A vertical prototype, on the other hand, offers functions in their intended final form, however, only selected functions are included.

2.2. A brief overview of prior research on prototypes and prototyping

Prototypes and prototyping research have a particularly strong and well-established role in the fields of software development and HCI. One example is Shackel (1959)—in one of the very first research papers on HCI—who used prototypes to determine optimal panel layout of potentiometers and switches in regard to operational performance. Applying a prototype-driven development process is nowadays considered best-practice within software development. Methodologies, such as agile software development, is fundamentally based on the principle of incremental and iterative development of prototypes (Martin, 2002). A prototype-driven approach for software development was also suggested by Boehm (1988). He argues that the standard waterfall model, which bears similarities to the stage-gate model in NPD, is far from optimal for developing new software systems. As a consequence he proposed an alternative which he named the "spiral model of software development". One of the main arguments was the lack of iterations considered in traditional waterfall models, which prevents implementation of new learning as the project progresses. Customer preferences (and product requirements) may change dramatically during the course of development which may take several months or years. Moreover, it is difficult to determine actual needs before a specific solution is tested out. The customer may even have the wrong request from the very beginning, not knowing exactly what is desired.

One obvious reason for the strong foothold of prototypes in software development is that creating a new iteration of a product (or module of the product), test, learn and use the generated information in the next version of a prototype is quick and cost-effective. Thus, iterative development with short feedback loops may be an effective way of developing new software products. Despite the fact that the majority of prototype-specific research is found in software development and HCI, prototyping has always been an essential part of design and engineering. According to Ullman (2010), the method of quick and small releases and subsequent fixes that has become popular and considered state-of-the-art within software development stems originally from the early days of mechanical engineering: the time "*. . .when something would be tried, broken, fixed, and tried again.*" (Ullman, 2010, p. 116). For complex physical products, however, the same prerequisites do not necessarily apply as feedback loops are typically longer and the cost of building and testing prototypes may be significantly higher. This does not imply that prototypes should not be used as a tool for learning, though; it rather means that it is even more important to understand how to effectively utilize prototypes and prototyping in the development process in order to save money and time and increase the value of products. Table 1 shows an overview of physical prototyping that have been studied in prior research. Few of these studies concern prototyping of products that have been launched to the marketplace, and even fewer concern complex products for high-volume applications. Thus, it is questionable if findings from these studies may be applicable for a product-developing organization.

2.3. The purpose of prototypes and prototyping

Most state-of-the-art NPD models emphasize prototyping in the late stages of the development process (Cross, 2008; Pahl and Beitz, 2007; Ullman, 2010). Here prototypes are commonly used as verification and validation tools of aspects of the product or the production process. Ullman (2010), for example, considers four types of prototypes: *proof-of-concept, proof-of-product, proof-of-process* and *proof-of-production*. The purpose is to *verify* and *validate* assumptions, expectations and calculations made at an earlier stage in the development process. In other words, an outcome that deviates from expectations is considered non-compliance and would thus call for corrective actions. This conception and use of prototypes is considerably different from that of HCI where it is common to create prototypes early in the development process to experiment with different solutions and explore the solution space. In this context unexpected outcomes are not deemed as failures, but rather important means for learning and communication. This difference may be illustrated by a quote from Lim et al. (2008): "*. . .a prototype is fundamentally different from the final product, whether or not it is identical to the final product. Prototypes are means and tools for design and are not the ultimate target for design.*"

Ulrich and Eppinger (2012) argue that prototypes serve four main purposes in a product development project: *learning, communication, integration and milestones.* Since learning and communication are recurring themes in a wide range of literature concerning prototypes, we will categorize prior research findings in these two categories.

Table 1
Overview of physical prototypes examined in prior research.

Source	Type of product	Timing in the development process	Type of prototyping	Launched to market	Prototypes – shape and material	Type/purpose
Buchenau and Suri (2000)	Digital camera	Early-stage, requirements	Exploratory experience design	Yes	Plastics and electronics – mixed fidelity	Determine early requirements, envision user experience
Hall (2001)	Card terminal for credit card purchases	Mid-stage, layout requirements	Interaction design	Unknown	Cardboard – low fidelity Plastics – high fidelity	Evaluate layout for interaction
Houde and Hill (1997)	Computer (laptop)	Early-stage, requirements	Interaction design	Unknown	Cardboard, pizza box	Evaluate form and weight
	Conference phone	Early-stage, requirements	Interaction design	Unknown	High quality plastic	Evaluate role (the product in use-context)
Horton and Radcliffe (1995)	Pineapple harvester	Early-stage, proof-of-concept	Engineering design	Unknown	Fischertechnik kit	Determine conceptual design and evaluate proof-of-concept
Sérgio et al. (2003)	Student project, washing machine	NA, student project	Engineering design	No	Electronics, fully functional washing machine	Teaching
Ulrich and Eppinger (2012)	PackBot robot	From early-stage to beta product	Engineering design	Yes	Polymers and analytical prototypes	Various, mostly evaluation of structural integrity
Yang (2005)	Student project, electromechanical design prototype	NA, student project	Engineering design	No	Electronics, aluminum, from kit	Determine if simpler prototypes result in better design

2.3.1. Learning

According to Ulrich and Eppinger (2012), two fundamental questions that prototypes may provide answers to are "*Will it work?*" and "*How well does it meet the customer needs?*" Prototypes often aid to answer specific questions involving user interaction. For example, by allowing intended customers handle the prototype for assessing usability (Rosenthal and Capper, 2006), incorporating customer feedback in the development process (Herstatt et al., 2006) or even allowing the customer to define functional prototypes throughout the development process (Campbell et al., 2007). In this context, the focus is on validating or verifying certain aspects of the design. In other cases, prototypes are also used to discover new aspects; ones that are unknown or not considered at the outset of the work. Bacon et al. (1994) found that prototyping led employees to discover various problems, or 'surprises', that would not have been uncovered in any other ways. In this regard, prototypes were found particularly useful for teams developing product systems in which testing of individual components is insufficient to determine if a system works or not. Floyd (1984) argues that prototypes may serve as a catalyst for eliciting good ideas while Yang (2005) found that prototypes often lead to new questions that were not considered at the outset of the work. Lichter et al. (1993) use the term *exploratory prototyping* to describe all prototyping activities that aim to clarify the problem.

One possible explanation for the efficacy of prototypes for the present purpose is pointed out by Ulrich and Eppinger (2012, p. 298): "*all of the laws of physics are operating when the team experiments with physical prototypes.*" Thus, the construction and testing of physical prototypes may uncover unanticipated phenomena.

Based on the findings above, it seems that prototypes aid learning in two distinct ways:

- Validation or verification of selected aspects of a design.
- Framing of design problems and exploration of various possibilities related to the design.

2.3.2. Communication

Prototypes are also known to facilitate communication in the NPD process. According to Ulrich and Eppinger (2012, p. 295) "*prototypes enrich communication with top management, vendors, partners, extended team members, customers and investors.*" Similar findings were reported by Bacon et al. (1994). They found that prototype construction aided intra-team and intra-firm communication as well as facilitating manufacturing process technology development. Verganti (1997) argues that early prototypes are one of the most effective mechanisms to foster discussion early in the design process. Here the rationale is to use early and rough prototypes to stimulate proactive thinking, rather than to test or verify detailed solutions. Many other researchers have also pointed out that prototypes are useful to communicate and explore ideas and concepts (Boujut and Blanco, 2003; Börjesson et al., 2014; Carlile, 2002; Dow et al., 2012; Lidwell et al., 2010; Schrage, 2000; Seidel and O'Mahony, 2014).

2.4. Prototypes in high novelty projects

Several studies have concluded that prototypes are particularly important when creating high novelty products. For example, Tidd and Bodley (2002) found that prototypes were useful for all types of projects, yet significantly more useful in high novelty design projects. Veryzer (1998) studied several radical innovation projects and found that prototypes were developed at an earlier stage that what is considered the norm in incremental projects. In radical innovation projects, development of prototypes typically preceded opportunity analysis, market assessment and financial analysis. Hence prototypes served more as a tool to *explore* rather than to merely verify preconceived assumptions. This is supported by the arguments of Quinn (1985), stating that innovative enterprises, whenever possible, move faster from paper studies to physical testing due to inadequacy of theory. Leifer et al. (2000) claim that 'radical innovators' frequently use prototypes in the early phases to interact with potential users. In this context physical prototypes are particularly useful because they often require little or no interpretation to be understood.

2.5. Pitfalls and limitations of prototyping

Although prototypes are invaluable tools in the design process, it is important to recognize the shortcomings and potential pitfalls of using prototypes. As mentioned above, prototype construction may be a time consuming and expensive endeavor, especially in the case of physical prototyping. One way to limit the resource usage is to construct rough, low-fidelity prototypes. Several researchers argue that low-fidelity prototypes can be helpful in the design of physical products (Buchenau and Suri, 2000; Carleton and Cockayne, 2009; Houde and Hill, 1997; Kelley, 2001; Schrage, 1993) as well as in HCI (Bailey and Konstan, 2003; Rudd et al., 1996). However, multiple studies also show that there are significant differences between low and high fidelity prototypes. For example, high-fidelity prototypes are known to be effective tools to communicate and advocate a design solution to internal stakeholders and management (Houde and Hill, 1997; McCurdy et al., 2006). If the goal is to elicit feedback from clients or potential users, however, high-fidelity prototypes tend to result in superficial feedback, often related to the appearance and detail rather than basic functionality (Landay and Myers, 2001; Maldague et al., 1998; McCurdy et al., 2006). Furthermore, McCurdy et al. (2006) argue that consistency along the fidelity dimensions is of critical importance.

Since it is apparent that there is a wide range of characteristics that influence how a prototype is perceived and what its applicability is, it is important to carefully consider and define the intent of the prototype. Is the aim, say, to assess functionality or to communicate a concept to the management in the organization or to explore alternative designs? For example, a 3D printed plastic engine intake manifold prototype may very well be adequate to communicate certain design aspects within the team. However, its rough surface appearance may not resonate equally well with top management, and specific precautions would need to be taken when using the part for engine testing due to substandard mechanical properties.

3. Research strategy

3.1. Case selection and method

The automotive industry was selected because it is a mature industry that develops and manufactures products that fit within the defined scope. Additionally, our previous studies on the automotive industry identified prototypes and prototyping as an important enabling capability in early-stage product and technology concept development, see Elverum et al. (2014). This study continues to build upon our former work by conducting in-depth studies on one of the identified enablers for viable concept development.

Based on the identified knowledge gaps and the research objectives given in the introduction, the overall goal of this work is to investigate the prototyping strategies used in the development of technically complex products for high-volume applications. It was chosen to limit the scope to products that have been successfully launched in the marketplace for validity, information availability and confidentiality reasons. Since incremental innovations build extensively on their predecessors, hence reducing the need for early-stage prototyping, only high novelty products were considered case candidates. Initially, four product innovations launched by the case company were identified as potential candidates for case studies: internal cylinder coating for aluminum engine blocks; a prototype fuel-cell vehicle; an inflatable seatbelt; and an aluminum panoramic roof module. After applying our screening criteria and discussing with project managers, the inflatable seatbelt and the panoramic aluminum roof module were selected for further in-depth studies.

We chose to employ a case study methodology since the organizational context is important and the nature of our research objectives are considered suitable to be answered with a case study approach (Yin, 2008). Furthermore, as identified above, knowledge on the role of prototyping in an industrial setting is scarce, which promotes the use of an inductive and exploratory research approach (Maxwell, 2012). Due to the lack of prior research on this topic, the most important factors were unknown at the outset of the work, which made a case study approach favorable to other alternatives (Eisenhardt, 1989). A qualitative case study approach can provide rich data by gathering information from multiple sources and particularly by capturing *anecdotal* data that enable us to fully understand and *explain* relationships (Mintzberg, 1979).

When conducting cases studies, it is recommended to employ multiple data collection methods and sources of evidence to increase the validity of the findings (Eisenhardt, 1989; Yin, 2008). The methods employed for data gathering were semi-structured interviews and graphic elicitation. Three main sources provided the input data for the study: interviews of employees in the organization, studies of physical artifacts and project documents. All interviews were conducted by the corresponding author. One interview was conducted via telephone while three interviews were conducted on-site at the case company. All interviews were audio recorded and transcribed. The qualitative data analysis tool QDA Miner by Provalis Research in combination with Microsoft Excel were used to code each transcription and search for links across the sample.

The interviews were performed in two rounds where the first round was used to go through the entire development process of the innovations, from initiation to implementation and product launch. The goal was to obtain an overview of the project and find points of interest to study more in-depth. Project documents were also identified, synthesized and studied at this point. The data obtained in the first round was used to acquire a comprehensive overview of the cases and construct an interview guide for the second round, see Fig. 1 for a more detailed sequence of tasks. The overview was visualized on a portable whiteboard that was used for graphic elicitation with the interviewees in the second interview round. To keep track of changes as new information surfaced, digital versions were also created, using Adobe Illustrator. See Appendix for the digital versions of the graphic elicitation.

3.2. Case company

The company behind the two product innovations examined in the case studies is among the top five automotive OEMs in the world measured by vehicles produced per year. Like most automotive OEMs, a structured phase-gate type development process is defined for developing new products and technologies. Although this process is not necessarily rigorously enforced, it serves as guidance to the development and management teams through a series of sequential checkpoints or gates. One of the most important aspects of following a structured process is to ensure that when a new product system, component or technology enters a vehicle program, it is sufficiently developed and proven so only acceptable risk prevails regarding technology readiness. The technology development process employed by the case company is divided into four main stages:

Discovery. This is the first stage in the development. The Discovery stage often includes fundamental research and exploration of various technology alternatives. Physical prototyping at this stage is not formalized but still happens frequently, usually on the initiative of the program champions.

Concept Ready. At the Concept Ready stage extensive prototyping is usually carried out. The goal at the end of this stage is to have a proof-of-concept ready, which is commonly demonstrated with a physical prototype. Additionally, preliminary Design Failure Mode and Effects Analysis (DFMEA), cost analysis and design verification are usually conducted.

Application Ready. At this stage the advanced development team is commonly involved with new-product development teams in order to assess the needs of product planning and work out a plan for implementation of the component or technology. This phase usually involves a higher level of functional prototyping since it is common to install and test the functionality of prototypes in vehicle builds.

Implementation Ready. When the final stage is completed, the component or technology is ready to enter a vehicle program. This does not mean that the product is ready to go on the market, merely that it is considered ready for further development toward implementation in a specific vehicle. At this point it is common to ‘bookshelf’ the component or technology until it is found attractive and affordable for a vehicle program.

4. Findings

4.1. Case background

4.1.1. Case 1: panoramic roof module

The panoramic roof module was the outcome of a project that initiated within research and development in 2007. Two senior researchers were discussing the use of lightweight glass in roof modules, realizing that the panoramic steel module offered at the time was far from optimal. So they started coming up with ideas to improve the design. The existing modules were manufactured out of several stamped steel sheets and consisted of many brackets, tracks and reinforcements. The use

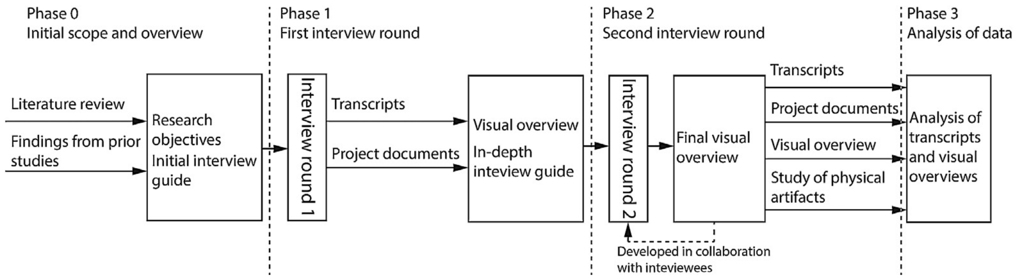

Fig. 1. Sequence of research tasks.

of steel made the roof module heavy and the stamping process required expensive tooling. Because the steel module was offered as an option on one of the company's larger vehicles, the high weight of the roof module was somewhat acceptable. However, extending the design concept to smaller mainstream vehicles would be impossible given the existing weight and cost characteristics.

Several design alternatives were considered; among them were aluminum modules, plastic modules and hybrid modules using a combination of plastic and aluminum. The main idea behind the aluminum design was to use extruded aluminum profiles for the side rails of the module. This would not only make the roof module lighter, but several functions could be incorporated into the extruded profile designs, which would result in fewer parts and a more integrated design. Additionally, unlike the stamped steel design, the aluminum design provided the flexibility to allow reuse between programs, accommodating the packaging requirements of several vehicle models. Because the aluminum design seemed to be superior from a structural point of view as compared to the plastic and hybrid modules, the R&D team decided to continue working on the aluminum design.

Initially, the team was aiming to apply the new lightweight design to the company's current line of Sports Utility Vehicles (SUVs) and so-called "Crossovers". However, the real need for a lightweight panoramic roof module arose after the completion of the Implementation Ready phase. The company planned to offer a luxury sedan where a steel design would be too heavy in the sense that it would affect the ride and handling of the vehicle. Two external suppliers were contacted and handed the requirements for the roof module, which they ultimately failed to meet. It was at this point the company brought one of their cooperative suppliers to the OEM's facilities and revealed the solution that the R&D team had been working on, which ultimately resulted in a successful market launch in 2013.

4.1.2. Case 2: inflatable seatbelt

The inflatable seatbelt was the result of a safety project that started in 1998, where the initial goal was to improve rear seat safety. Several field studies on driving factors indicated that rear seat usage was increasing. This insight along with an aging population was the main motivation factor for the project. Due to fragile bones, elderly people are more prone to bone fracture which might result in severe injuries or even death by relatively moderate collisions. Also, several medical issues prevail when it comes to recovering from bone fracture of elderly people.

Early on in the project, attempts were made to transfer existing airbag technology to the rear seats. This was unsuccessful and the team continued to work on alternative concepts before a new idea of integrating an airbag into a seatbelt was discussed. In addition to providing increased rear seat safety, an inflatable seatbelt could potentially prove to be a less expensive and less complicated system than standard airbags, thus making the technology suitable for the emerging markets in developing countries.

Background research revealed that a number of studies were conducted on inflatable seatbelts in the 1970s, see for example Burkes et al. (1975), Fitzpatrick and Egbert (1975), Lewis (1974) and Walsh (1976). Although all of the studies found that an inflatable belt resulted in less severe injuries than a standard 3-point seatbelt, neither of the systems were feasible as a product in terms of manufacturability and packaging.

The project team realized that recent advances in airbag technology and inflation methods could potentially overcome the barriers that the systems faced in the 1970s. The team found a company that was currently working on a similar technology and decided to partner up with this company for the development of the product. The product was first introduced in a production vehicle in 2011, thirteen years after the project initiation.

4.2. Case comparison

In this section detailed storylines of the two cases are presented and compared to each other in order to highlight the main differences between the projects throughout the development stages. To organize the findings, the data, including coded transcriptions, are presented using the stages of the technology development process as a basis. Generic aspects of the development are covered in this section, but with the emphasis on prototypes and prototyping.

4.2.1. Discovery

Since the two projects had considerably different starting points and goals, the Discovery phases were quite dissimilar. In Case 1 the goal was to design a panoramic roof module, which was an improvement of an existing module design. In Case 2, however, the problem statement was open-ended, pushing the team to look at widely alternative concepts. Among these were extra wide seat belts and traditional airbags applied for rear seat usage. After evaluating the different alternatives, it was decided to continue with the inflatable seatbelt concept. Prototypes were not constructed at this stage in either of the projects.

4.2.2. Concept Ready

In Case 1, the first question that the team had to answer was if it is possible to replace steel with an aluminum alloy while maintaining structural integrity. Although the aluminum design was radically different from the existing steel design, assessing structural integrity is a well-defined problem within a context where extensive knowledge and tools already exists. Therefore, digital prototypes could be established by using finite element analysis (FEA) to determine feasibility in terms of strength, stiffness, durability and dynamics. Computer simulations for the entire vehicle were conducted with a surrogate aluminum roof module. At this stage torsional stiffness, bending stiffness and crash properties were analyzed.

Several iterations were necessary to optimize joint configurations and profile geometry in certain areas. The Project Champion expressed that he has a fair amount of confidence in computer-aided simulations for these types of problems. However, the only answer the simulations provided was that the design would most likely work if it was installed in a vehicle, given that it was possible to manufacture the roof module to the desired quality and cost targets.

In Case 2, however, there was very limited existing knowledge that could be used to assess the feasibility of the concept. Would it have a positive effect on the passenger in a collision impact situation? If an effect could be observed, what were the governing mechanisms behind this effect and how could these potentially save peoples' life? To find answers to these questions, several 'cobbled up', physical prototypes were made. Cobbled up, as expressed by one of the interviewees, essentially means that off-the-shelf parts were extensively used to assemble a rough yet functional prototype to save money, time and minimize commitment to a specific concept due to the investments made. The prototype was then tested in sled tests with crash test dummies to measure and document a variety of effects. In both cases, initial prototyping efforts (digital or physical) provided the teams with enough confidence to proceed the development.

4.2.3. Application Ready

In the Application Ready phase, extensive prototyping was carried out in both cases. In Case 1, after validating the feasibility of the concept with FEA, it was recognized that the extrusion of the profile for the side-rail was one of the main critical aspects on which the (technical) success of the design concept relied. Since the cross-section for the side rail was highly complex, consisting of several chambers, outstanding flanges and functional details, the feasibility of extruding the profile within the required accuracy in relation to the dimensional tolerance requirements and target cost was in question. Some early testing was done in-house before an external supplier company was contracted to perform the initial prototyping of the extrusions. After proving sufficient capability in extruding the profile, the next critical operation was to bend the extrusion into the curvatures of the vehicle's roof contour while maintaining the dimensional accuracy required for functionality, both in manufacturing, in-use and service. Because the outcome of the bending operation is dependent on the extrusion shape (cross section and sweep), as well as bending method and multiple process and control parameters, several iterations of both the bending technique and the extrusion die were necessary at this point. For example, wrinkling was initially a problem but an acceptable result was obtained after four iterations.

In Case 2, the team continued to conduct experiments on the 'cobbled up' prototype to further understand the multiple cause–effect scenarios such as the bag size and resulting load distribution. Small changes were made to several parts to achieve the desired functionality, e.g., by changing the size of the gas inflator. One of the most time consuming challenges in this phase was to identify and test for all the various failure modes and potential scenarios of use and misuse. Failure mode and effects analysis (FMEA) schemes for a standard seatbelt and an airbag were used as a starting point. However, these do not by any means cover the entire FMEA for an inflatable seatbelt. To identify additional issues for the FMEA scheme, prototypes were actively used. The importance of prototypes at this stage may be illustrated by quoting a statement made by one of the interviewees: "*Unless we built the prototype we didn't know the FMEA, because it's a new system.*" Prototypes were also mediators for identifying use and misuse scenarios, as illustrated by quoting one of the respondents: "*We don't think of all the scenarios before we make the prototype. We think of certain scenarios, we make the prototype and we use the prototype to come up with the other scenarios*. . . *the most effective way we get the scenarios is when we give it to a customer and let them play with it. And they actually come up with scenarios we haven't even thought of, and they do that all the time.*" At several occasions, users' interactions with prototypes led to the identification of scenarios that the research team did not initially think of. One example is the 'toolbox test': "*One of the test that we had to look at was when the tradesmen used these vehicles they opened the back door and threw in their toolbox; so we do a toolbox test to make sure that these buckles are sturdy enough. I mean, things that most of us in research won't even think about at the concept stage. And every aspects of those tests influences the design because it changes the material, it changes the design.*"

The prototyping in the Application Ready phase varied considerably for the two projects studied herein. While the focus in Case 1 was limited to testing specific aspects of the design, the prototyping efforts in Case 2 were of a more exploratory nature, including extensive contact with users to identify and test for a number of a priori unknown scenarios.

4.2.4. Implementation Ready

To reach the sign-off at the *Implementation Ready* gate, extensive testing, verification and validation is required. In Case 1, after completion of the extrusion and bending prototypes, several fully functional prototypes of the roof module were made. To save time and money, the team used new parts in combination with production parts from the existing roof module. Six vehicles were outfitted with the prototype modules and tested extensively. Noise, vibration and harshness (NVH), durability, rough road, torsion and bending were among the tests conditions that were considered. Essentially, all testing required for new roof modules was carried out at this point and the design was finally assessed to provide a sufficiently high technology-readiness level for further implementation.

The Implementation Ready phase for Case 2 was far from straightforward as the team experienced several setbacks. Although the system conceptually worked flawlessly during a functional crash test, there were concerns with several aspects of day-to-day operation. One of the most serious problems in this regard was the placement of the gas inflator. The weight of the inflator exerted a slight force on the belt, causing an unpleasant and constant pressure on the chest of the user. Using a set-based approach, six alternative methods of delivering gas to the bag were tried out. Although every one of them worked conceptually, they all failed in day-to-day operation or in meeting vehicle packaging criteria. It was at a moment after one of the failures that one of the interviewees had a 'eureka moment', as he described it himself. Why not run the gas through the anchor and buckle? This outside-the-box idea was not initially well-received by the rest of the team and there was immediate resistance toward going down that path. Despite the skepticism, three team members decided to proceed exploring the idea as their own unofficial 'skunk work' stunt. An initial concept was sketched out using CAD software, and a prototype was made using stereolithography (SLA) technology. Even though this prototype was non-functional, once the rest of the team could see the conceptual prototype they were convinced that this concept could possibly work. Several iterations of 'cobbled up' functional prototypes were required to make the bag successfully deploy with gas fed through the anchor and the buckle. The second major usability issue was the thickness of the inflatable bag. Attempts to overcome this problem included looking at other industries for inspiration and possible solutions, among them was the women's stocking industry for bag production. This issue was not resolved until one-piece woven technology for producing airbags became available on the market.

After the Implementation Ready phase, the path to vehicle integration was substantially different for the two innovations. In Case 2 the team had broad support from management throughout the entire development, whereas in Case 1 the project was funded and commenced on the initiative of the Project Champion without the upper management's awareness. Therefore, the Project Champion decided to build and test a comprehensive system prototype extensively before he went to the management of vehicle development asking for support. In other words, the final prototype in Case 1 was used as a means of persuasion.

4.3. Overall comparison

The two innovations differed considerably with regard to development time. The total time from initiation to market availability was five years for the panoramic roof module and thirteen years for the inflatable seatbelt. The significant difference can be attributed to the level of newness of the inflatable seatbelt, and the fact that it is a safety product that requires extensive testing. Although the panoramic roof module was a substantial improvement over the existing panoramic roof modules, the inflatable seatbelt was an all-new innovation in a product category that has never existed before and therefore relied on the development and convergence of several technologies to succeed. According to the definition of innovation by Garcia and Calantone (2002), the panoramic roof module can be categorized as a 'really new' innovation as it required new technology and production process without creating any new markets. The inflatable seatbelt, on the other hand, can be classified as a 'radical' innovation. In this case the product entailed the development of all-new technology and seen from a market point of view, an entirely new product category as well.

The risk-level from an organizational point of view, however, is not associated with merely the newness of the innovations themselves. Because both innovations are parts of a larger system (the vehicle), risk has to be seen from a local (project) as well as a global (vehicle) view. As an isolated project, the inflatable seatbelt was unquestionably more risky with a lower chance of success. On a vehicle-level, however, there was less risk associated with the inflatable seatbelt. Failing to implement the system into a vehicle would not result in major setbacks as it was possible to fall back to a standard seatbelt. The panoramic roof module, on the other hand, is highly integrated into the structure of the vehicle and thus critical to the overall vehicle performance. A failure to implement this product would result in a costly setback for the particular vehicle program. A comparison of the two innovations highlighting the key differences is shown in Table 2.

5. Discussion

In this section, we will synthesize and extract the most important findings in our study and relate the findings to existing literature. We attempt to extract the essence of our findings to provide a basis for transferability to other contexts than the one investigated herein. An overall synthesis of our findings will then be presented in a proposed model: directional and incremental prototyping. Finally, we will discuss the implications of our findings in managerial terms.

5.1. Prototyping strategies

5.1.1. The importance of considering the phenomena

A comparison of the two cases investigated shows that the prototyping approaches employed were fundamentally different, yet, both proved to be viable approaches. In Case 2, early prototypes are found invaluable in helping the development team to understand a new system, especially when the amount of prior experience is limited. A technical system can be highly complex and the overall function cannot be predicted by merely analyzing the components in isolation (Hubka and Eder, 1988). The internal and the external conditions in which the system operates are important factors that govern performance and behavior. In this regard system prototypes can enable the team to learn whether the system works or not and discover unforeseen consequences. One of the interviewees in Case 2 made the following statement: "*One of the huge advantages to early conceptual level prototypes is you see the unintended consequences and the system interactions.*" In this particular setting, the prototype acted as a test bed for the team to answer the critical question as to whether the system worked or not. This finding expands on, for example, Ullman (2010) and Ulrich and Eppinger (2012) where these prototypes are referred to as *proof-of-concept prototypes* whose basic intention is to answer whether the concept works or not. In this case, however, the product concept was not merely proven to work conceptually. By constructing and testing a physical prototype of the integrated system, the team were able to determine that the concept provided the necessary capability to operate in the real world. Constructing a comprehensive system prototype early on in the project may be perceived as counterintuitive and a departure from traditional thinking of

Table 2
Comparison of the two innovations.

Project	Project/innovation characteristics				Prototypes constructed in the various development phases			
	Risk-level	Development time	Level of user interaction	Context predictability	Discovery	Concept	Application	Implementation
Case 1: panoramic roof module	Local: high Global: high	Five years	Low	High: well-defined requirements that need to be fulfilled, established tests regimes	None	Digital, FEA	Physical, prototypes of the most critical aspects (extrusion and bending)	Physical, fully functional to validate the design
Case 2: inflatable seatbelt	Local: very high Global: low	Thirteen years	High	Low: difficult to predict the various scenarios of use and misuse, no pre-defined test regimes	None	Physical, 'cobbled up hardware', entire system	Improvements of the initial prototype Physical prototypes in contact with users to elicit requirements	Further improvements of the initial prototype SLA prototype to communicate radical design change

starting out with less extensive physical prototypes and even digital models. However, it is important to stress that the *phenomena* in this case was not well understood. That means that digital prototypes may be of limited or no use in the early phases since they require deep a priori understanding of the real-world phenomena. As pointed out by Wilkinson (2007, p. 22), a set of questions need to be answered before creating a CAE model, for example: "*...is there confidence that the results will be sufficiently accurate to support the decisions that will be based on them?... are the real-world operating conditions understood and can they be replicated in the model?*" If the phenomena are well-understood and models already exist, the strategy described below may be more suitable than constructing a comprehensive systems prototype.

In Case 1, a considerably different approach was used in the early phases. Since the innovation to be developed was less radical and the phenomena were well understood, a more traditional strategy could be employed. In addition to extensive use of digital tools, the team built several less expensive (focused) prototypes to reduce uncertainty by answering specific questions in the early phases. One of the interviewees referred to this as "pre-prototyping": "*If you can make the extrusion and make it straight. That was the first prototype. Once we do that, maintain the dimensional geometry, bend it and maintain the dimensional geometry again, then we knew that we could make the prototype. That was kind of the, I guess I would call pre-prototyping.*" These pre-prototypes sought to answer specific questions critical to the design and manufacturing capabilities instead of assessing overall performance and functionality. In other words, the problem was divided into smaller, testable problems. Because of the intent of these prototypes—answering a single specific question—we refer to these prototypes as *critical function prototypes*. A similar characterization of prototypes is used in related literature. For example, Ulrich and Eppinger (2012) refer to the type of prototypes that look only at selected functions of a system as *focused prototypes*. One advantage of this approach is that focused prototypes may be less resource intensive to construct than a full system prototype while providing full functionality on specific aspects of the design. This will not only result in fewer resources spent, but also less favoritism of a particular solution at an early stage (Sobek et al., 1999), less sunk cost and less design fixation (Viswanathan and Linsey, 2013). However, this approach requires awareness of the overall system interactions, i.e., the interaction between the components. Thus, it is an approach that may be more suitable in situations where the phenomena are well understood and substantial knowledge and prior experience can be utilized.

5.1.2. Using prototypes as exploratory tools to identify scenarios and incorporate contextual requirements

The high level of user interaction and low level of context predictability led the team in Case 2 to use prototypes to elicit information regarding the use (and misuse) by potential users. The purpose of this activity extended beyond what is considered traditional user interaction in the literature. For example, Herstatt et al. (2006), Rosenthal and Capper (2006), Patanakul et al. (2012) and Ulrich and Eppinger (2012) consider the purpose of user interaction to be testing the usability of the design and determining if the customer needs are fulfilled. In this case the purpose was not only limited to assessing usability of the product, but to detect unanticipated *scenarios*. Thus, prototypes were actively used to identify unknowns. More specifically, the team used prototypes to identify a priori unknown scenarios of use and misuse that could not be identified by merely discussing within the team and eliciting existing knowledge. In other words, the team used prototypes to go from a set of unknown unknowns to known unknowns (Ramasesh and Browning, 2014). For example, one user expressed a concern that his dog would chew on the belt and puncture the bag. To test this potential failure mode, the belt was soaked in meat juice and given to a dog to chew on it before it was tested in a crash test. This is just one example of a host of insightful scenarios and potential failure modes that were elicited from users in interaction with prototypes. Once the unknowns are identified requirements can be established and formal tests can be designed to ensure fulfillment of the requirements. In this particular example, the new insight led to a formal test routine where the bag is intentionally punctured before being subjected to crash tests. It is important to stress that there are also other ways of uncovering usage scenarios. Interviews with potential users and observational studies of people using regular seat belts are just two of the approaches that may be useful to gather insights regarding use-scenarios. However, allowing individuals to interact with physical prototypes may lead to insightful discoveries (Lim et al., 2013).

5.2. Prototypes to communicate within the organization

5.2.1. Communicating within the team

Prototypes were frequently used to communicate, both within the team and with stakeholders outside of the team. One of the most interesting findings, which appears contradictory to traditional engineering design literature (e.g., Pahl and Beitz, 2007; Ullman, 2010; Ulrich and Eppinger, 2012), is the usefulness of low-fidelity, non-functional prototypes late in the development process. The SLA prototype that was created during the implementation phase in Case 2 had a considerable impact on the outcome of the project. A possible explanation of the efficacy of the low-fidelity prototype in this incident might be that the team was left with few alternatives, and thus willing to take the risk. The alternatives were either to continue exploring the seemingly infeasible radical proposal of running the gas through the buckle; or start working on a backup solution that could result in years of setbacks and possibly lead to a compromise in product performance. Nevertheless, with the help of a simple non-functional prototype the team managed to convince their colleagues to explore a radical design change late in the development process. This finding implies that even the simplest prototype may be better at conveying and persuading members of the team than drawings and digital prototypes.

5.2.2. Communicating across the organization

The Project Champion in Case 1 stated that one of the main reasons for building and testing such a comprehensive systems prototype was to convince management and increase the likelihood of bringing the product to market. A great deal of former research argue that prototypes—in particular high-fidelity prototypes—are powerful tools to influence decision-makers, for example, Berghel (1994), Kelley (2001), Schrage (1993), Virzi et al. (1996). A possible explanation of the efficacy of high-fidelity prototypes is explained by Schrage (1993, p. 7): "*Good ideas may be rejected by ill-informed executives based on what is perceived as inadequate execution of the prototype. Top management may find it difficult to see beyond prototype roughness to the ultimate product.*" Our findings support this body of research as the final prototype in Case 1 was actively used as a mediator to communicate the value of the new design to the decision makers. Due to the novelty of the design, the team was faced with skepticism when proposing it to upper management. One of the respondents explained this situation as follows: "*You are telling me 25 pounds lighter, 11% increase in stiffness and it is cost neutral? At one point they thought we were out of our minds. Well, here is the prototype. We made the prototype, we tested it. It was functional and people can get into the vehicle and use it.*" The demonstration of the prototype and the data gathered from the testing removed doubts and concerns that the vehicle executives had regarding the feasibility of the design. As a result, the strategy of using comprehensive prototypes to persuade decision-makers was successful as vehicle development decided to adopt the product for one if its vehicle programs: "*He* [Chief Engineer, body exteriors] *really liked the prototype and all the verification testing. He had the comfort level of, wow, not only did you do the prototype, but you had all of this testing and you are telling me you are pretty much ready to go. And the answer was, yes.*"

The major decision point involved not only technology readiness but also as to whether or not to implement the system into a major vehicle program. Moreover, since the panoramic roof module is a highly integrated part of the body-in-white build, as opposed to a 'hang-on' component, the prototype needed to authenticate that the risks (technical, financial and market) were mitigated to an acceptable level. In other words, the prototype reduced the uncertainty from the management's and vehicle program's point of view and was the main reason for accepting such a radical design change. The importance of the prototype in bringing this component to market was clearly stated by one of the interviewees: "*Without the prototype, this would not be on the vehicle. The physical prototype, without it, it's worth nothing.*"

5.3. Directional and incremental prototyping – a proposed model

The two cases investigated demonstrate how prototypes are used in the development of two novel innovations. To explain how teams use prototypes to drive the development forward, we propose an explanatory model that consists of two distinct types of prototyping. We have named these two types of prototyping as *directional* and *incremental* prototyping. Details of the proposed model is described below and exemplified by our findings in Case 2.

Whenever the team is working on a new, unproven design, directional prototyping serves as guidance and a tool for evaluating the direction in which the team is heading. Directional prototypes can be used for initial feasibility assessment of the concept. In Case 2, the team constructed a rough but functional system prototype that defined the technical direction of the project. One of the interviewees expressed the following: "*Right at the beginning when we saw some of the benefits, we spent a lot of time trying to understand why does it work. And as soon as we knew why it worked there was a strong, what shall I say... we believed in the technology.*" Even though the team was not certain that the concept would work, the directional prototype provided 'good enough' results to keep the team moving in that particular direction. Once directional prototypes are constructed, tested and partly understood, a series of *incremental* prototyping follows.

The purpose of incremental prototyping is to optimize the design and further increase the understanding, without making considerable changes to the overall design. In this particular case, incremental prototyping consisted of experimentation with various aspects of the prototype which was already constructed. One example is experimentation with various parameters related to the gas supply. The type and the size of the inflator were modified to fine tune deployment of the bag as well as further understand the effects during an impact. After it was discovered through extensive user testing that the design would not function in everyday use, the team was forced to completely change the existing concept. This led the team, once again, to explore new solutions and construct a *directional prototype*.

The SLA prototype (as previously mentioned) was a directional prototype as it required major changes to the overall concept. Although the SLA prototype was non-functional, it changed the overall direction by convincing the team to support a radical design change. This is further elaborated by one of the interviewees: "*The challenge was to turn around people's thinking about what a buckle and a tongue can do. Because it is not just a buckle, it is a tongue also. They have all been trained to think it is a mean to lock a belt into the buckle. Nobody has paid attention to can I use this for something else?*" After the team was convinced of the new direction, a series of prototypes were constructed to determine the feasibility of the radical design change. Once again, a 'cobbled up' prototype was made, followed by a series of prototypes with incremental changes. The challenges associated with the first 'cobbled up' prototype are illustratively described by one of the interviewees: "*We built the first prototype... it didn't happen the first time. We had quite a few challenges of gas delivery through the buckle, even though it was delivered through the buckle and the tongue; the bag blew out so there was lots of those mishaps.*" Fig. 2 illustrates this model by classifying the various prototypes created in Case 2 in these two proposed categories. Here it is important to note that the directional prototypes in this case occurred both at the team level (where the conceptual idea was introduced) and at the technical system level (where the technical solution is assessed).

5.4. Managerial implications

One of the core implications from this study is that prototyping needs to be accepted and encouraged as a part of the organizational culture when aiming to develop novel products. The success of both product innovations investigated herein relied strongly upon prototypes. Besides the proof-of-concept prototypes, which served to answer questions such as 'will it work', prototypes were used to communicate and persuade. For example, in Case 1, the innovation would most likely never be adopted by a vehicle program without the comprehensive testable prototype used to convince the management. In Case 2, compromises on product performance and delayed product launch would have been the result if the team had not been persuaded by the low-fidelity prototype as a motivation for making a radical design change in the late phases.

Prototypes are found to be effective means to persuade and one of the main reasons for that is their role in reducing uncertainty. Criscuolo et al. (2013) and Masoudnia and Szwejczewski (2012) found that one of the reasons why employees resort to bootlegging (i.e., conduct R&D activities with no formal organizational support) is to delay the assessment of embryonic concepts and ideas. Experienced researchers know that an early idea or concept is unlikely to get managerial support if uncertainty prevails. Here, building and testing prototypes is an effective way to preliminary assess and demonstrate a concept with regard to technical feasibility and usability. Seen from a risk management point of view, thus constructing early *directional* prototypes *prior* to a project kick-off may greatly reduce uncertainty and increase the success rate of new development projects.

The study found that, despite recent advances of digital tools, physical prototypes are still of major importance in the development of novel products. Therefore, from a managerial point of view, prototyping should be regarded as source for learning, risk mitigation and ultimately innovation rather than merely an expense (late) in the development process. In other words, early prototyping could benefit the innovation process by identifying unanticipated problems and mitigating risk through front-loading (Thomke and Fujimoto, 2000). Thus, the ultimate goal should not be to eliminate physical prototyping entirely since digital tools build exclusively on existing knowledge; hence, digital tools' potential for confirming compliance

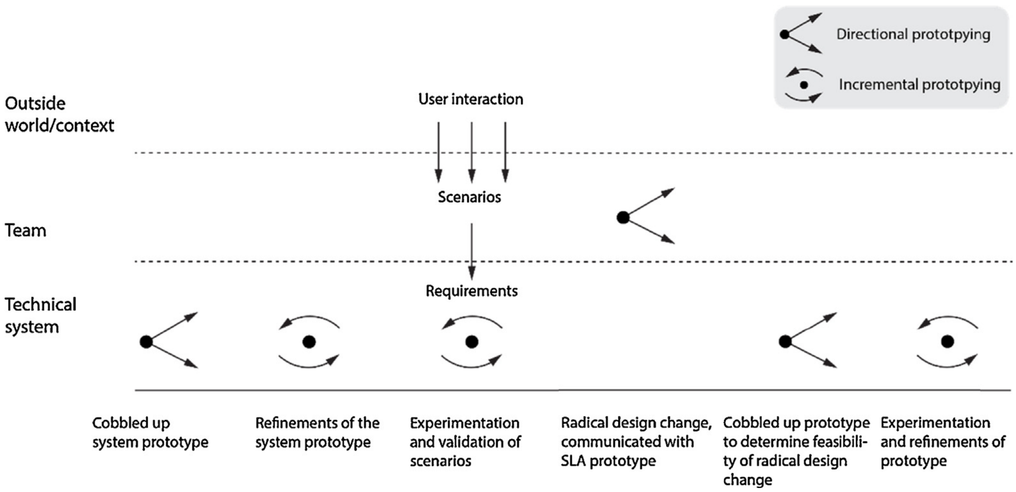

Fig. 2. Directional and incremental prototyping in Case 2.

with the 'known' is significantly higher than their potential for exploring the 'unknown' in the creation of novel solutions. Since risk and uncertainty in the early phases typically stems from inaccurate or wrong information, eliminating perceivably 'unnecessary' activities—such as prototype builds—may lead to initial cost savings but have a significantly negative impact on the overall outcome due to late discovered problems, incompatibilities and lack of differentiation from current product offerings (Browning, 2003).

Another implication to consider in this connection is the positive effect of conducting prototyping internally within the organization. Besides the learning aspect, the organization contains intellectual property generated internally within the organization. Toyota Motor Company, for example, is known to use in-house development as a strategy to build the organization's knowledge on systems and components (Nonaka and Peltokorpi, 2006). By following this strategy and building prototypes internally, the knowledge gained from initiation to validation of a design is kept within the walls of the organization. This knowledge combined with the prototypes can then be used as a basis for co-development with suppliers. As exemplified in Case 1, it is possible for the OEM to have a strong influence on the design while 'pushing' the supplier beyond its original capabilities. Here, the design can be patented before approaching the supplier to keep the intellectual property rights with the organization and make further use of the prototypes constructed.

6. Conclusions, limitations and future work

This study sets out to explore prototype usage and prototype strategies used during the development of novel products. Two exploratory case studies of recent product innovations launched by a major automotive OEM were conducted to attain this objective. In the two cases investigated, prototypes were found to aid communication and learning both within the development team and across the organization. In particular, prototypes were found to be powerful means to persuade both external decision-makers and members of the development team. With regard to learning, the teams actively used prototypes for both verification and validation purposes, in addition to exploring usage scenarios and eliciting requirements by allowing users to interact with the prototypes. The development teams in the two cases employed considerably different prototyping strategies. In the first case, the strategy was characterized by extensive use of digital prototypes followed by the construction and testing of several physical, critical function prototypes. In the second case a comprehensive physical system prototype was created early on in the project to determine feasibility and assess the overall functionality of the concept.

Based on these findings, a model that consists of two distinct types of prototyping: directional and incremental, is proposed. Directional prototyping serves to assess and advocate for solutions that entail major changes to the overall design. Once directional prototypes have been tested and understood, partly or entirely, incremental prototyping follows. Incremental prototyping enables a deeper understanding and finally a validation of the design—without changing the overall design direction.

This study demonstrates that prototyping efforts in engineering design encompass more than 'verification and validation' purposes, typically made with the motivation to ensure compliance with requirements or legislations, which is commonly found in traditional engineering design literature. Finally, it is concluded that physical prototyping is an important activity in the development of novel products providing a larger potential for exploration of the unknown than digital prototypes.

In this study, it was deliberately chosen to use an in-depth case methodology, focusing on a single industrial context instead of aiming to generalize across industries. While internal validity is maintained by triangulating data from interviews, project documentation and physical artifacts, generalization of findings outside this particular context is limited. The study is also limited to encompass only novel products, ignoring more traditional, incremental product development. Furthermore, since this study draws upon only two cases within a single organization, it is uncertain if our findings represent 'best practice' or not. However, the fact that both innovations were successfully developed and launched in the marketplace for one of the most competitive and quality-driven industries is a strong indication that the strategies employed by the development teams are viable and may be transferable to other contexts as well.

While both product innovations investigated herein may be regarded as 'novel', our findings indicate that there are a number of characteristics that influence what prototypes to create and how to approach prototyping. For example, the level of user-interaction and use-context predictability appears to strongly affect the need for prototyping and dictate what strategy to employ. Future studies should continue to explore how various factors influence the need for prototyping activities, and identify appropriate strategies to prototyping in different contexts.

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Appendix

A.1. Graphic elicitation/timelines from the two cases investigated

Figs. A1 and A2.

Fig. A1. Digital version of TSPM for the roof module.

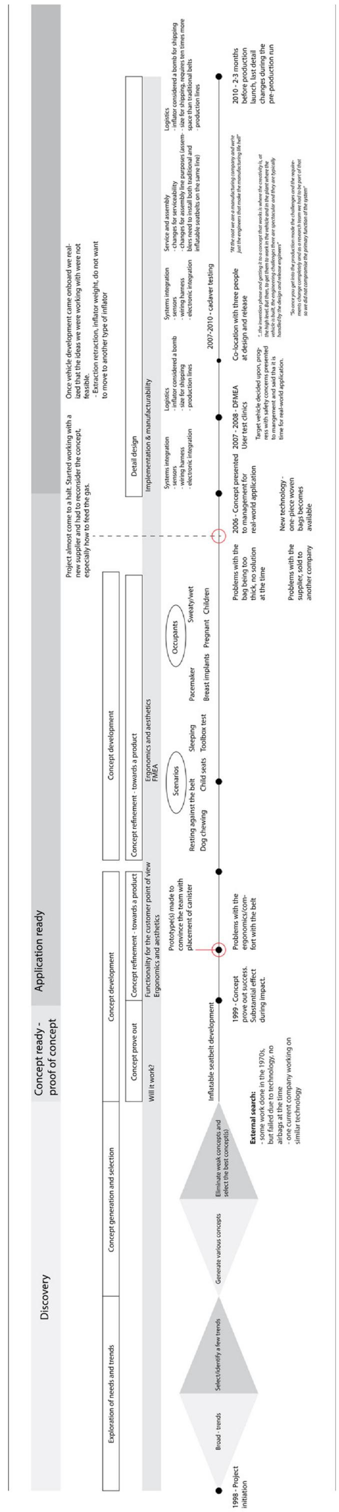

Fig. A2. Digital version of TSPM for the inflatable seatbelt.

B.1. Case evidence – images and models of the product innovations investigated

Figs. B1–B3.

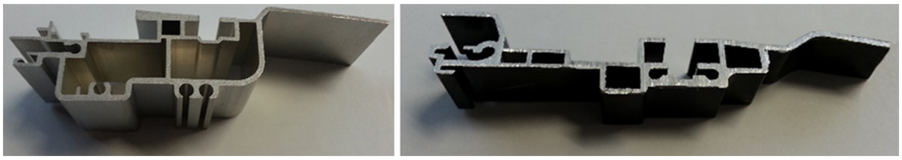

Fig. B1. Cut out of the extruded side-rail for the roof module. Prototype (left), actual product (right).

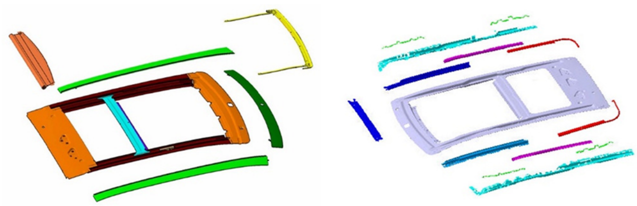

Fig. B2. Exploded view of the roof modules. Systems prototype (left), original steel module (right).

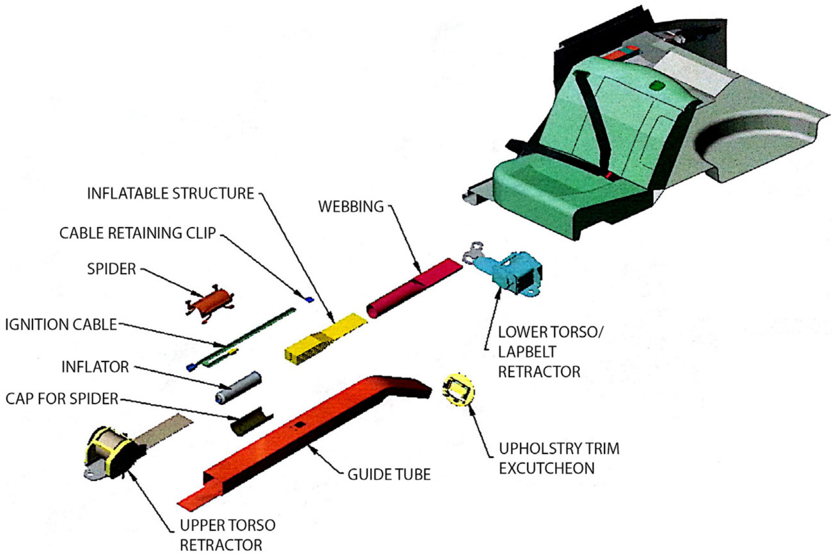

Fig. B3. Exploded view of the original inflatable seatbelt design.

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