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Prototyping in new product development: Strategy considerations

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Abstract

Prototyping is an important activity in most new product development processes. Whether the aim is to explore new opportunities or refine existing solutions, prototyping can be a valuable tool. This paper takes a look at the diversity of prototyping practices and the contextual factors that may have an impact on the prototyping strategy. Through existing literature and industrial as well as academic case studies, several prevailing contextual factors are identified and used as a basis to propose guidelines to aid practitioners in making important decisions when formulating a prototyping strategy.

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Keywords: prototyping; new product development; product systems; prototypes; engineering design

1. Introduction

Prototyping is an activity and a tool that has received considerable attention in the product development research communities in recent times. With the increasing interest in adopting Design Thinking (DT) in various business and product development domains, early-stage prototyping has become an important activity. Contrary to the 'proof-of-product' role that prototyping often is given in traditional engineering design [1], prototyping in DT takes on a more exploratory role. As pointed out by Seidel and Fixson [2], instead of validating ideas, prototyping can be used to stimulate imagination [3] or be used as a tool for "building to think" [4]. Thus, the speed of prototyping and subsequent testing become critical factors. Available technology has played an important role with regard to prototyping capability in the development process. Combining digital and physical prototyping such as in *mixed prototyping*, for example, has great potential for developing and evaluating the usability of product interfaces [5]—a critical aspect of most new product systems. By utilizing digital tools, it is possible to create highly flexible prototypes that enable short learning cycles at an affordable cost.

Regardless of whether the prototyping medium is physical or digital, it is important to choose the right strategy for prototyping. In the context of new product development, Ulrich and Eppinger [6] provide useful information for product developers by outlining important principles of prototyping [6, p. 297] and propose how prototypes should be planned for in a product development project [6, p. 303]. These guidelines can be a valuable overview and starting point for product development practitioners who wish to learn more about prototyping in general and, more specifically, utilize prototyping as a tool in the development process. However, considering the breadth and diversity of the research on prototyping, there seem to be a need for a synthesized overview that collects research from the various research domains and provides insights for product developers. Additionally, it is crucial to identify predominant contextual factors in order to make sound strategic decisions.

Therefore, the purpose of this paper is twofold:

- To provide researchers and practitioners with a brief overview of prototyping research in various domains that may have great impact on new product development and shows promise for future research.
- To take the first step towards a strategical framework consisting of contextual elements and practical principles for carrying out prototyping in a product developing organization, thus expanding on the work by Ulrich and Eppinger [6].

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This topic is investigated and strategic guidelines are proposed by revisiting the data from two previous industrial case studies, see [7] for more details. Additionally, two recent cases where prototyping was actively used in the early development stages in a far more exploratory manner are included in the sample.

2. The diverse roles of prototyping

The research on prototyping branches out into a wide variety of research domains. From engineering design [1, 6, 8] to human-computer interaction (HCI) [5, 9-13], Design Thinking [2, 14, 15] and software development [16-18]. To illustrate the diversity and give the readers an overview of the various roles that prototyping takes on, brief descriptions are given below.

2.1. Engineering design

Prototyping in engineering design usually serves a wide variety of purposes. The most common being to verify and validate assumptions, calculations and decisions during the development, as well as answering two fundamental questions: “Will it work?” and “How well does it meet the customer needs?” [6]. The perhaps most common use of prototyping in engineering design is the development of “milestone prototypes” that often are denoted “proof of” prototypes, as well as alpha, beta and pre-production prototypes [1, 6]. Early-stage prototyping is often not formalized and is performed when ‘deemed necessary’ by the development teams. Although, some companies are known to extensively use formalized prototype-driven approaches in the early phases [19, 20].

2.2. Human-computer interaction

In HCI, prototyping is given an integral role in the overall development process and prototyping is acknowledged to “Support creativity, helping the developer to capture and generate ideas, facilitate the exploration of a design space, and uncover relevant information about users and their work practices” [9, p. 122]. Since HCI deals with human behavior and interaction, prototyping is a useful tool to ensure that the user is involved in all phases of development, for example through participatory design [21].

2.3. Design thinking

In DT, prototyping take on quite a different role. Here the main purpose is commonly to facilitate the development and transform novel ideas into preliminary models that can be evaluated [2]. Prototyping—in the very early phases—can also be used as a tool to “get going” by building to think [4]. In this sense, DT is a prototype-driven development process or philosophy. It is common for development teams to build and test prototypes from the very beginning in a project. This means that the speed is crucial. How fast the team is able to build prototypes, test prototypes and implement lessons learned in the next iteration is a critical factor for progress.

2.4. Software development

Much like HCI and DT, prototyping in software development can have an integral role in the overall development process. Since software is not physical, working through multiple prototype iterations and thus using prototypes to drive the development process forward can be a cost efficient and viable development approach. The ‘movement’ that believes in a prototype-driven process (e.g., Agile Software Development) [22] stands in stark contrast to the former, more traditional waterfall approach [23] where planned iterations are avoided.

As can be seen from the brief descriptions above, prototyping is a versatile tool that may take on many roles and can be used in the very early as well as in the late development stages. Since the focus of this paper is on developing physical product systems, the remainder will revolve around physical prototyping.

3. A brief overview of the cases

This section gives a brief presentation of four case studies. The data in Cases 1 and 2 are revisited from a prior study [7]. These cases were the study of two product systems that were developed and produced by an automotive OEM. Cases 3 and 4 are early-stage development projects that are conducted as a collaborative effort between academia and the industry.

3.1. Case 1 – Prototyping in the development of a panoramic roof module

The panoramic roof module was a novel design developed by the OEM in collaboration with an external supplier. Prototyping in this case take took place after careful CAD and FEA studies ensured confidence in the design. Several critical function prototypes were developed and tested to explore and ensure manufacturing capability since the design was unproven.

The project was commenced on the initiative of two experienced engineers within research and development. In the final stages, a comprehensive system prototype was developed and thoroughly tested to gain support from executive management, thus increasing the likelihood of implementation in production vehicles.

3.2. Case 2 – Prototyping in the development of an inflatable seatbelt

The inflatable seatbelt was developed by the same automotive OEM as in the previous case. The product system was a breakthrough new-to-the-world innovation when it was first introduced in the marketplace. With a total development time of thirteen years it was a challenge that relied on maturation of several technologies to be successfully developed.

In this case, the development team prototyped extensively throughout the development process. Due to the newness of the product, digital prototyping was not used in the early phases to evaluate the concept. The team instead made a series of ‘cobbled up’ prototypes to test whether the concept would work or not, and then prototyped to further refine the design. One of the perhaps most interesting and surprising findings in this case was the major influence a non-functional 3D printed prototype had in the late implementation stage. A few members of the development team managed to convince the rest of the team to adopt a seemingly 'impossible' solution to avoid usability problems with the existing design.

3.3. Case 3 – Early-stage prototyping of personalized public transport

In this case, the development team consisted of twelve students from three universities sponsored by a corporate organization. The challenge was open-ended and one of the directions the team explored was 'personalized' public transportation. Since this exploration of the project's overall direction took place in the very early phases, there was a strong focus on spending as little time and resources as possible.

To gain insights into this particular direction, the team employed a prototype-driven approach and built a series of rough prototypes that were tested in real-life scenarios. The team figured out that one of the critical questions that needed to be answered was how it would *feel* to have a personalized and private space in public transportation systems. For these types of questions, *experience prototyping* [24] may provide important answers and insights and aid the team in evaluating the promise of the direction. Fig. 1 shows some of the evolutionary experience prototypes that were built and tested on buses and trains. These simple and crude prototypes took a very short time to create and test. Yet, findings from the user testing provided the team with sufficient data to make several critical decisions to progress the project.

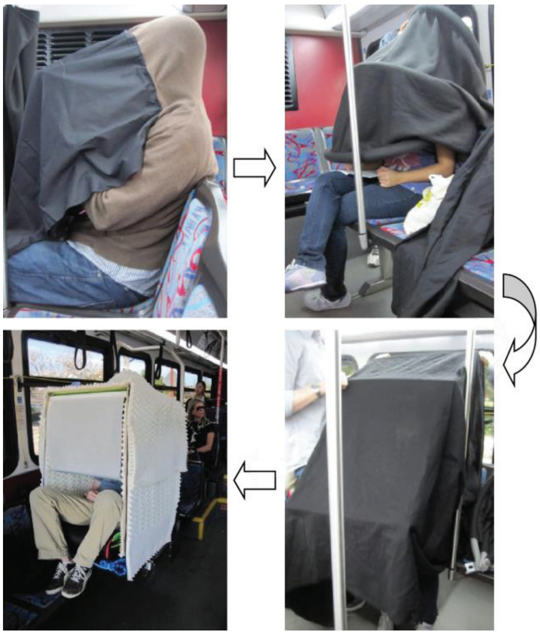

Fig 1. Evolutionary experience prototyping of personalized public transport.

3.4. Case 4 – Early-stage prototyping in the development of a mobile flood protection system

Similar to the previous case, the prototyping in this case took place in the very early phases of a development project. The development team consisted of two students, one researcher and two external consultants. The scope of this project was considerably more defined than in Case 3, and the goal here was to get familiar with the problem and gain practical experience and insights on working with fluid-structure interactions. One of the main questions the team wanted to answer was: *'how simple and rough can we make small-scale prototypes and yet manage to achieve realistic behavior with regard to sealing against ground surfaces?'*

Again, since this took place very early in the project, there was a focus on iterating fast and inexpensively to quickly learn without committing to any particular solutions.

Fig. 2 shows some of the many prototypes that were constructed and tested. The top row of the figure shows the two main system prototypes that were made to find the critical level of approximation. In the first image the team simply used a small pool, tape and cardboard. Despite the fact that this did not work at all, the test provided the team with valuable information early in the project. This led to the building and testing of a more rigid, modular setup that could be reused several times. The more elaborate prototype enabled focused testing of parts of the system, as shown in the figure below.

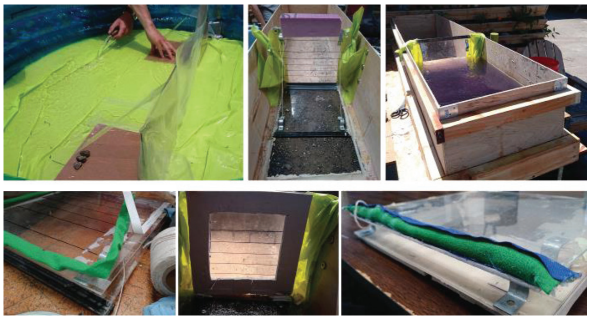

Fig 2. Small-scale prototyping of mobile flood protection systems. Prototyping of the entire product system (top row), focused prototyping of a subsystem (bottom row).

4. Contextual factors that shape strategy on an organizational level

With prototyping—like any other aspect of product development—the context plays a critical role in determining a suitable approach. It may be dangerous to make decisions without understanding the context. In order to make sound decisions regarding a prototyping strategy, it is necessary to identify the governing contextual factors. In this regard, the context is considered to be the surroundings and the entire setting or situation a manager, engineer or any other person may find himself or herself in when planning to prototype. It is obviously not possible to provide a complete overview of all contextual factors; the purpose here is to list the most prominent ones from existing literature and the case studies.

4.1. The organizational culture – specification-driven prototypes vs. prototype-driven specifications

This is perhaps one of the most important factors when it comes to prototyping strategy. It is also one of the factors that is hardest to measure and to change. Schrage [25] discusses the difference between the organizational culture of entrepreneurial startups and large, mature organizations when it comes to prototyping. One of the major cultural differences in this regard is whether a company operates with specification-driven prototypes or prototype-driven specifications. This fundamental difference is embodied in the overall culture, as well as the business context and the business model of the company. Some companies have cultures (or behaviors) that see prototypes as the end result of the specifications that are defined over the course of the development, whereas other companies are more prototype-driven and see prototypes as more of a 'living specification' with great potential to explore various possibilities.

We argue that these two extremes represent the very basics of how prototyping is approached and will shape how an organization or a development team view and use prototyping in its product development efforts. Ultimately, this may have a major impact on the innovative capability. It is, however, important to point out that one is not necessarily better than the other; it depends on the context. For example, an organization in a mature industry developing incremental product innovations may not benefit from operating with prototype-driven specifications due to the high degree of prior knowledge and experience present. Conversely, an entrepreneurial startup with little prior experience and knowledge working on a new-to-the-world product may leverage working through multiple early-stage prototypes and thus employ a prototype-driven specification approach.

Because of the downstream consequences of the entire development process, it is paramount that the balance between these two extremes is carefully considered when formulating a prototyping strategy. Based on the case studies and related work [26], it seems that most development projects require the capability to handle a combination of the two extremes. As a general rule of thumb, when exploring possibilities and opportunities in the early phases, learning-cycle (takt time) is of essence and a prototype-driven approach like those employed in Case 3 and 4 may be favorable. With a high degree of existing knowledge and experience, however, a more specification-driven approach as in Cases 1 and 2 may be the wiser choice.

4.2. Audience

As stated by Schrage [25, p. 10], a Silicon Valley company's edict is "Never show fools unfished work". This illustrates the importance of being cautious with showing or demonstrating early prototypes to the wrong people. Findings that support this claim were made in Case 1 where the development team worked on the new product 'in the dark', without management's knowledge. The project champion pointed out that had he shown the management any of the work too early, the project might have been shut down before they could demonstrate the true potential of the revolutionary design.

Other researchers have also emphasized the importance of taking the audience into account, see for example [10, 13, 24, 27]. The type of audience will usually affect important decisions regarding the construction and presentation of the prototype. As stated by Buchenau and Suri [24, p. 431], "Knowing the audience and their expectations helps determine the resolution and fidelity of a prototype." As a general rule of thumb high resolution prototypes are preferable when seeking to impress, persuade or gain feedback from a less expert audience [13, 27], while low-resolution prototypes are more suitable for gaining early feedback (including criticism) from experts that may lead to substantial design changes.

Here it is important to point out that it may be misleading to use a prototype merely as a means of persuasion; for example, by presenting a flashy looking prototype simply to convince other stakeholders. On the other hand, if the high-resolution prototype is highly functional and used as a feasibility demonstrator, like in Case 1, it can be an effective risk mitigation tool.

4.3. Timing in the development process

The timing in the development process is often referred to as one of the main dimensions that dictate the prototyping efforts [6, 10, 25]. The general belief here seems to be that prototypes become gradually more functional and refined throughout the development process. This may be generally true if one is looking at prototyping of the entire product system. However, aspects of subsystems or unanticipated problems can arise late in the development that may call for more rough types of prototyping. One example of this is the non-functional 3D printed part that helped influence design decisions in Case 2.

5. Towards a contextual prototyping strategy

In this section, the lessons learned from the case studies along with existing theory are brought together to propose a starting point for a contextual framework to aid practitioners in developing a prototyping strategy. Considerations and suggestions that are vital when developing a prototyping strategy are listed below.

5.1. Define the purpose

The single most important point when developing a prototyping strategy is to define the purpose of the prototyping. What questions need to be asked? What questions need to be answered? This will help refine the *intent* and the *purpose* of the prototype or prototyping activity. This may seem like an obvious starting point, but it cannot be stressed enough how important it is to be *deliberate* with defining the purpose and identifying critical questions and knowledge gaps.

5.2. Identify important project-level contextual factors

Based on the aforementioned case studies and literature, the following are some of the most important project or product specific contextual factors that will influence the prototyping strategy.

- The amount of prior knowledge and experience with the problem or product system in question.
- The (use) context predictability.
- The level of user interaction.

To be more specific, one example when the strategy is affected by the contextual factors listed above can be found by comparing Cases 1 and 2. In these two cases, the contextual factors are considerably different. In Case 1, there was extensive prior knowledge as well as experience for the type of product to be developed, whereas in Case 2 it was an all-new product to the company and to the world. Furthermore, in Case 1 the context predictability was high whereas the level of user interaction was low. All these factors, in turn, led the development teams to employ, equally viable yet vastly different strategies. In Case 1, prior knowledge and experience could be utilized to achieve the following:

- Keep the amount of physical prototyping to a minimum and utilize digital tools.
- Create several focused or 'critical function' physical prototypes to answer important questions instead of creating (more expensive) comprehensive system-level prototypes.

5.3. Keep it simple

This is a key principle in any good prototyping practice, especially for early-stage prototyping where the overall direction of the project may change. It may seem obvious to keep things as simple as possible, but it is encouraged to spend some time on identifying the absolute simplest, easiest and cheapest way to answer the critical questions and thus fulfill the prototyping purpose. One example is the initial prototyping in Case 3. By focusing on simplicity and the core question(s) that needed to be answered (experience of personalized space), the resulting prototyping was very simple, quick and inexpensive. Although Case 3 illustrates that simple prototyping can be valuable, it may seem that this principle is difficult to utilize when developing more complex products in an industrial setting. However, a good practical example where this principle was extensively used on a daily basis and contributed to creating breakthrough innovations was at Lockheed Skunk Works. Despite dealing with extremely complex product systems, a lot of the prototyping efforts that enabled the company to succeed in building these product systems on budget and on time were often banal and on the borderline of being stupidly simple. One example of early-stage prototyping was during the development of the F-117 Nighthawk stealth attack aircraft, as explained by Ben R. Rich, former director of Skunk Works:

"We knew that this slightly newer and larger shape would be as unstable as the Have Blue aircraft— but would there be differences? To find out, one of our aerodynamicists built a giant slingshot that looked like a rock-hurling catapult right out of an old Robin Hood movie, set it up on the third-floor ramp of a huge assembly building the length of two and a half football fields—and then fired off models of our new stealth shape and took slow-motion film of how they fell to the ground, receiving a painless preview of what would happen if the real airplane spun out of control. Security forced us to do this indoors rather than off a rooftop—but it worked perfectly." [28, p. 85]

5.4. Acknowledge the power of 'cobbled up' prototypes

Another important principle is to acknowledge the value of 'cobbled up' prototypes. By 'cobbled' up we mean prototypes that are mainly built from off-the-shelf parts. With extensive use of off-the-shelf parts, it is possible to move quickly and avoid spending too much money and at the same time create highly functional prototypes. This principle was extensively employed in Case 2 and allowed the development team to create and test comprehensive, fully functional prototypes, even in the early stages.

5.5. Proposed initial contextual strategy guidelines

Some proposed initial guidelines are shown in Table 1. Here it is suggested to divide the proposed guidelines in categories based on the context level and the contextual factors themselves. In this example, only one context level is considered: the product system/project.

Table 1. Proposed strategy guidelines.

Context level	Contextual factors		Proposed guidelines
Product system/project	Degree of prior knowledge and experience	High	Take advantage of non-physical prototyping (e.g., simulations). Consider using vertical/focused physical prototyping to answer critical questions.
		Low	Focus on early (comprehensive) system prototypes. Consider extensive use of cobbled up prototypes, especially if a high degree of functionality is needed.
		Very low	Focus on speed and quantity. A large number of (rough) prototypes with subsequent testing can result in valuable learning cycles. Consider employing a highly prototype-driven process, especially in the early phases.

4. Conclusion, limitations and outlook

This paper set out to investigate prototyping in new product development with the goal of providing contextual factors and guidelines to aid prototype strategy formulation. Through existing literature and four case studies, important contextual factors were discussed and several prototyping guidelines were proposed.

The intended use of a strategical framework is to provide practitioners with actionable and concrete proposals for developing and implementing a prototyping strategy in development projects. It should however be noted that the intent is not to prescribe a 'recipe' for prototyping.

Although several contextual factors were identified in this study, there are a host of other factors that will influence the strategy. Furthermore, a topic not discussed, is how the context can be altered. If the prototyping is being planned and initiated by individuals high up in the organizational hierarchy, there is a great chance that they have the potential to influence the context and the organization's capabilities and thereby change the context.

Since the data are based on case studies, it is impossible to claim any particular efficacy of the proposed guidelines. Even though the approaches were viable in each of the cases, other strategies and approaches might have proven to work just as well.

Future work should continue on this path, to study prototyping in practice and identify important contextual factors. A considerable number of prototyping studies have been published in the last decade and there is a need to tie together and interpret this research to come up with practical methods and guidelines for organizations to take advantage of prototyping as a tool. Finally, we suggest that future research should employ a variety of research methods and continue to build on the small framework for strategical guidelines that is presented in this article.

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