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CASE STUDY: EVIDENCE OF PROTOTYPING ROLES IN CONCEPTUAL DESIGN

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ABSTRACT

The goal of this research is to investigate prototype use in conceptual design. In order to begin this line of study, we look first to current practices in industry. A case study involving two companies provides examples of prototype use in the conceptual design phase of their respective product development cycles. Six interviews were conducted at two different companies in order to help understand how prototypes are used by industry during the conceptual design phases of a product development process. This research finds evidence that prototypes are being used successfully in conceptual design, even though typical literature sources advise against it.

Keywords: prototyping, conceptual design, case study

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1 PROTOTYPING IN CONCEPTUAL DESIGN

The goal of this research is to investigate prototype use in conceptual design. Conceptual design activities are those that are at the fuzzy front end when information required for parametric sizing and geometric configuration is not available (Pahl et al., 2007). In order to begin this line of study, we look first to current practices in industry. A case study involving two companies provides examples of prototype use in the conceptual design phase of their respective product development cycles. The companies are selected to verify the findings across industries and the plurality of interviews within the companies are used for triangulation. This is a preliminary, exploratory study that serves as the motivation for more detailed empirical studies in prototyping in conceptual design.

Prototypes have been defined in many ways. For instance, prototypes are models used to show the form and feel of a product (Hyman, 1998) or are full-scale pre-production models used for testing functionality and manufacturing processes (Dieter and Schmidt, 2009). Others define prototypes as models or representations of either components or systems (Buchenau and Suri, 2000; Dieter and Schmidt, 2009; Hannah et al., 2008; Hyman, 1998). Rather than defining prototypes along a system dimension, others argue that prototypes are approximations used to explore one or more aspects of a product, such as functionality or look and feel (Ulrich and Eppinger, 2008). Some definitions extend the definition of prototypes from physical to graphical, analytical, or graphical media (Buchenau and Suri, 2000; Clarkson and Eckert, 2004; Hannah et al., 2008). Essentially, prototype definitions address: scope, role, and media.

In this paper, prototype is any physical model used to represent one or more aspects of a product. In addition, the prototyping process encompasses all activities related to the conceptualization, design, fabrication, and use of the prototype. A prototype may be a custom fabricated assembly to closely mimic the final design, while a common household object used to represent something else in a discussion could also be considered a prototype. In this way, the focus of this research is not just physical traits, but how the physical nature of an artifact relates to a role during conceptual design.

While prototypes can be useful throughout the engineering design process, there are some potential pitfalls and drawbacks, such as time constraints, cost constraints, and design fixation (Dow et al., 2010; Dym and Little, 1999; Eggert, 2005; Otto and Wood, 2001; Pahl et al., 2007; D. Stowe et al., 2010; V. Viswanathan and J. Linsey, 2011; Youmans, 2011). To use prototypes effectively at any stage in a design process, these issues must be mitigated successfully. This paper focuses on the conceptual design stage, where less research regarding prototyping exists and the potential benefits to the project outcome are large.

The relationship between time and cost investments in an idea and the fixation or over commitment to that idea has been explored (Christensen and Schunn, 2007; V.K. Viswanathan and J.S. Linsey, 2009; Youmans, 2011). More specifically, fixation can be tied to the sunk-cost associated with building the particular prototype (V. Viswanathan and J. Linsey, 2011). In this research, experimental subjects who spent more time and effort prototyping were more likely to fixate than participants that used less expensive, in terms of effort, time, and cost, physical prototyping methods. It was also found, in a separate experiment, that low cost and low fidelity prototypes provided sufficient information to evaluate feasibility of concepts when compared to higher fidelity prototypes (Hannah et al., 2012), though the confidence in these evaluations were lower. Thus, prototyping in the conceptual stage has shown benefits in terms of maintaining design flexibility (countering fixation) without degradation in information utility. These conclusions are further supported when considering software and user experience product prototypes (Davis et al., 2006; Gordon and Bieman, 1995; Houde and Hill, 1997; Schneider, 1996; Virzi et al., 1996). Researchers have found that low-fidelity prototypes that are rough, fast, and inexpensive can be as useful as detailed, fully functional, high-fidelity prototypes (Holmlid and Evenson, 2007; Virzi et al., 1996).

2 CLASSIFYING PROTOTYPES

Several different methods of classification have been proposed and used by researchers while studying or instructing on prototype use. By classifying prototypes in terms of their physical characteristics or the activities they support, researchers are able to understand, discuss, and analyze work relating to prototypes and their use more effectively. Several classification schemes are presented here to illustrate the different ways prototypes are viewed as well as to define the classification used in the industry case study.

A common classification of prototype roles has four broad categories based on the activities they support (Ulrich and Eppinger, 2008):

- **Learning:** This role, one of the most common, includes testing the function of a prototypes and identifying potential problems.
- **Communication:** Prototypes can be used to communicate aspects (form or function) of a design to other team members, superiors, clients, or potential customers.
- **Integration:** Prototypes can be used to test how different components fit together and interact with each other to form a complete product.
- **Demonstration:** Prototypes are used to show progress on a design project or as milestones.

Researchers identified nine roles of physical hardware in design activities, such as discussion, communication, thinking, and visualization, through verbal protocol studies and observations of students as they developed new kitchen scales (Brereton and McGarry, 2000; Brereton, 2004):

- **Starting Point:** a starting point for conversations, ideas, and questions,
- **Chameleon:** different objects in different environments can take on new meanings and roles,
- **Thinking Prop:** nearby objects can encourage new ideas,
- **Episodic Memory Trigger:** encourage recall of memory related to the object,
- **Embodiment of Abstract Concepts:** links to other systems and fundamental concepts,
- **Adversary:** illuminates errors and misconceptions in thinking,
- **Prompt**: incites discussions, questions, and ideas,
- **Medium for Integration:** testing integration of objects and building mental models, and
- **Communication Medium**: demonstrations, persuasion.

From an educational perspective (Lande and Leifer, 2009), three themes in how students use prototypes are:

- **to clarify** ideas and concepts and to visualize their concepts.
- **to learn** and therefore refine their designs, especially in regards to understanding physical principles.
- **to guide** and motivate the students; iterating and improving the prototypes served as project milestones.

Others argue for the use prototypes and physical objects as inspiration for new ideas and concepts (Kelley, 2001) with justification based on current ad-hoc and informal practice at IDEO design firm. To support this, the company maintains a collection of interesting materials, mechanisms, and objects to use for inspiration on new projects.

In addition to classifying prototypes based on their roles or purposes, taxonomies have been created to describe each unique prototype from other perspectives (Hannah et al., 2008; Lande and Leifer, 2009; D. Stowe et al., 2010). A common goal is to use the taxonomies to identify trends and discover which prototype or process characteristics influence the effectiveness or success of the prototype. For instance, two high level characterizations are used in (Hannah et al., 2008):

- **Factors** are the considerations taken into account when fabricating a prototype (purpose, budget, design stage).
- **Characteristics** describe the prototype state due to the factors affecting its fabrication (size, material, fabrication processes).

Each of these characterizations are decomposed into detailed studies of the prototypes that include information about the prototype, the process, and the use. Alternatively, the Hierarchical Morphological Prototype taxonomy was developed to support case study analysis of prototyping activities, requiring lower levels of details to describe the prototypes (D. Stowe et al., 2010):

- **Variety -** Physical, Non-Physical
- **Complexity -** Component, Sub-System, System
- **Fidelity -** Form, Basic, Detailed, Realistic

As a result of requiring less information, the HMP taxonomy can be more subjective, especially when classifying the fidelity of the prototype. However, the taxonomy is sufficiently broad to apply to a variety of prototypes while still providing a consistent vocabulary to discuss and describe them. This taxonomy will be used throughout the case study to describe prototypes in a consistent manner.

3 INDUSTRY CASE STUDY

Literature describes potential benefits and drawbacks to prototyping, but discussion of prototype use in conceptual design and idea generation is limited. In order to study the use of prototypes to support these early stages of design, a case study was completed at two companies to document the types of prototypes used and how prototyping activities fit into their design processes. Within each company, three semi-structured interviews were conducted with engineering professionals to discuss the use of prototypes throughout their product development process. At the request of the participating companies, details of the interviews are restricted to prototyping activities and the roles fulfilled by the prototypes. Therefore, examples are discussed in general terms to protect the intellectual property and to respect the confidentiality request of the companies. All interviews for this case study were conducted at the respective companies' facilities - either in the interviewee's office or in a nearby conference room. Due to the semi-structured nature of the interviews, the discussion often deviated from the planned questions. Also, new questions were added as necessary to discuss topics from previous interviews.

The goal of the interviews was to gather information on prototype use during conceptual design, but it was necessary to address the entire development process at each company to understand the goals, constraints, and influences of the conceptual design activities. The questions prompted discussions on characteristics of the prototypes as well as how and why they were used. Additionally, these interviews aim to evaluate the value of prototypes in the overall design process and in conceptual design specifically. Figure 1 includes the structured questions used in the interviews in addition to the anticipated follow-up clarification questions. Transcripts are found in (Hess, 2012).

1) Can you talk a little about your role within the company and within the product development process?
2) Can you describe one of your most successful recent physical prototyping projects?
   a) Describe the product, the phase of development, what about the product was being prototyped? Was there any iteration of the design and/or prototype?
   b) How was the prototype made? Can you describe the process, materials, cost, who was involved?
   c) How would you describe the purpose of this prototype?
3) Can you describe one of your least successful recent physical prototyping projects?
   a) Describe the product, the phase of development, what about the product was being prototyped? Was there any iteration of the design and/or prototype?
   b) How was the prototype made? Can you describe the process, materials, cost, who was involved?
   c) How would you describe the purpose of this prototype? Common classification: milestone, integration, learning, communication.
4) What differences between the two projects most affected the outcome?
   a) Were there differences in the prototyping method (tools, materials, etc.)?
   b) Were there organization or team differences that affected the outcome?
   c) Were there differences in the purpose, role, or type of prototype that affected the outcome?
5) In your organization, how are decisions made concerning the prototype process?
   a) How do you decide what, how, and when to prototype?
   b) Is there a standard method or process for developing prototypes in the organization?
   c) What design project aspects are considered and influence prototyping decisions?
6) For the examples provided in questions 1 and 2, how did the process or outcome of the process differ from the expectations at the beginning of the process?
   a) Did your path forward in the project change as a result of prototyping?

Figure 1 Case Study Interview Question Protocol Defined a Priori

Each interview was analyzed to classify the prototypes discussed using accepted taxonomies described in Section **Error! Reference source not found.**. The prototypes were first classified according to the Hierarchical Morphological Prototyping (HMP) options taxonomy because it is broadly applicable and can be used effectively with limited information. (D. Stowe et al., 2010; D.T. Stowe, 2008). As the only data available for this classification is collected through discussions in interviews, this taxonomy is used because it was found be comprehensive while requiring less information than other taxonomies (Hannah et al., 2008; Michaelraj, 2009; D. Stowe et al., 2010). The roles of the prototypes discussed were also classified according the categories: learning, communication, integration, and demonstration (Ulrich and Eppinger, 2008). The third set of information extracted from the interviews is the set of design needs fulfilled by the prototypes. This set of design needs was developed by Stowe to describe the most common needs of designers that are addressed by prototyping and compliments the role classification (D.T. Stowe, 2008). Each prototype discussed in the interviews was classified by each of these taxonomies.

Automotive Supplier Interview Analysis

At Automotive Supplier, interviews were conducted with a project manager along with two cured tire designers. All three men work in a group responsible for taking tire concept designs, refining them, and preparing a set of suitable alternatives for another group to industrialize and take to market. The new tire development process at Automotive Supplier consists of several phases. In each consecutive phase, the concepts from the previous phase are refined, prototyped, and tested. The main phases are:

- **Concept:** In the concept phase, the designers are attempting to use new technologies or push the boundaries of the normal design practice to maximize different tire performances such as traction, wear-life, or handling. Often, a design change may improve a performance aspect drastically, but also cause unreasonable drawbacks in other performance aspects. These early tires are not ready for market. This is mainly a divergent stage focused on exploring many different possibilities and generating a large amount of information as well as pushing performance boundaries as far as possible. Depending on the maturity of the technology, physical prototypes might be used to validate new principles, such as non-pneumatic (Rhyne and Cron, 2006; D. Stowe et al., 2008, 2010).
- **Development:** The development phase is focused on taking information learned from the concept phase and building prototypes for one or two tire sizes (with multiple options for each size). This involves iterative testing and tuning of the tire design to create the desired combination of performance specifications. The development phase shares some characteristics with both convergent and divergent design phases. On one hand, the designers are trying to narrow down the number of concepts to be developed in the next stage of the design process. However, they are also often pursuing new design concepts to break compromises that the concept design group was not concerned with while trying to maximize various performances.
- **Industrialization:** The industrialization group takes the industrialized tires from the development group and industrializes the designs in all of the different needed tire dimensions.

The overall product development cycle at Automotive Supplier can take up to ten years from concept to market. This long time-frame is due in part to the large cost associated with building a new tire mold and the time put into thoroughly evaluating each mold and each tire that is to be built and tested. Also, due to the complex interactions between tire components, it is difficult to prototype and test components or sub-assemblies with meaningful results that will translate into a full tire. Additionally, there is a significant safety risk associated with passenger car tires. It is extremely important that the tires are safe for consumers as well as the drivers employed to test the tires. Therefore, the vast majority of prototypes that are built are full-size, complete tires. Example prototypes that were not full-scale included a hand-made clay model used to visualize tread features and rubber samples used for material testing and characterization.

Each prototype discussed with the engineers at Automotive Supplier is classified in Table 1. With the exception of one, all were physical prototypes. These physical prototypes tended to be either complete systems or single components, which is expected due to the complex nature of tires. Individual components can be tested for things like material properties while the complete system can be tested to understand the interactions between components. It was noted in the interviews that it is difficult to relate the results of a sub-system test to the results of complete system test. The prototype summary in Table 1 also shows that the majority of prototypes filled learning roles, relating to both performances and unknowns. While the prototypes helped meet a large variety of design needs, the majority of prototypes met needs relating to evaluation and analytical development. Intuitively, these results support the idea that the prototypes are taking on the learning roles in order to fill these needs. The conceptual related taxonomy elements of interest are shaded in the tables. Four of the five taxons have populated evidence from the Automotive Supplier.

A change to a single component of a tire can affect the entire tire and multiple performance characteristics. AS_1 described how it is difficult for the engineers to reliably predict all of the effects of a design change due to the complex interactions of components. This complexity is why prototypes use to develop or improve analytical models is a recurring theme throughout the interviews. The engineers are continuously correlating data back to the model results to make sure that the predictions are as accurate as possible and to improve the tools for future work.

Another theme from the interviews relates to the amount of planning behind building a set of prototypes. Due to the expensive nature of building prototype tires, all available analytical tools are used to refine designs initially and the prototype request must undergo an extensive review to evaluate costs and risks associated with the designs. This systematic method is followed for every set of prototype tires that is produced.

Table 1 Summary of prototypes discussed at Automotive Supplier

			Interviewee			
			AS_1	AS_2	AS_3	Total
Number of Prototypes			7	2	5	14
HMP	Variety	Physical	7	1	5	13
		Non-Physical	0	1	0	1
	Complexity	System	5	1	2	8
		Sub-System	0	0	1	1
		Component	2	1	2	5
	Fidelity	Realistic	3	0	1	4
		Detailed	2	2	2	6
		Basic	1	0	1	2
		Form	1	0	0	1
Roles	Learning	Performance	7	1	3	11
		Unknowns	2	2	3	7
	Communication	Functionality	1	0	0	1
		Configuration	0	0	0	0
		Visual/Tactile	2	1	1	4
	Integration	Assembly	0	1	0	1
		Refine Function	0	0	0	0
		Refine Process	0	2	1	3
	Demonstration	Customer Demand	0	0	0	0
		Milestones	1	0	0	1
Design Needs	Experimental	Analytical Development	3	0	1	4
		Evaluation	4	1	2	7
	Validation	Proof of Concept	1	1	0	2
		Proof of Product	0	0	0	0
		Proof of Procedure	0	1	1	2
	Selection	Aesthetic	0	0	1	1
		Conceptual Level	2	0	0	2
	Interrogation	Configure System	1	0	1	2
		Optimize	2	0	0	2

Automotive Supplier also produces multiple prototypes at a time to more effectively explore a design space. While using a single mold, the internal tire components can be changed with less expense to create new tires and explore different options. These activities are aimed at trying as many different options as possible while keeping the cost of the prototypes as low as possible.

A large part of exploring the given design space in tire design is trying to what the Automotive Supplier engineers called breaking compromises. Due to the complexity of pneumatic tires, almost any design change that results in the improvement in one aspect of tire performance is accompanied by a decrease in another aspect of tire performance. For example, changes to improve traction are often detrimental to rolling resistance. The act of breaking a compromise allows for the improvement of one performance aspect while not hindering another performance aspect that would normally suffer. Again, this is due to the complexity and inter-connectedness of the tire components. Being able to find a change that is the exception to the rule is critical for evolving the capabilities of tires.

Appliance OEM Interview Analysis

At Appliance OEM, three people agreed to be interviewed. Two of the participants, AP_1 and AP_2, worked in the product development department which was managed by the third participant, AP_3. AP_1's role is that of a technology scout, to find new technologies and concepts that could be used in novel ways in future products. AP_2 is the manager of the group responsible for the design of doors and cabinets for the refrigerators. This distribution of participants provided an overview of the product development process and prototyping philosophy at Appliance OEM while also providing details about specific projects and prototypes down to a component level.

AP_2 described the stage-gate process that is followed for the product development cycles at Appliance OEM. The process consists of four stages, each on culminating in a prototype build. During each stage, the design, production methods, and tooling are refined until the product is ready for production. The four stages described by AP_2 are described below:

– **Stage-0 Build:** This build is used primarily as a learning experience for the engineers. It is used to verify concept feasibility as well as fit and finish of designs. It is then used to focus efforts for development leading up to the next build.
– **Stage-1 Build:** The Stage-1 build is for "proof-of-design". Parts from the previous build are redesigned and parts that require functional testing and verification are usually tooled parts. Some aesthetic parts may still be of a prototype nature.
– **Stage-2 Build**: In the Stage-2 build, more of the parts are made from production or pre-production tooling to verify the manufacturability and ease of assembly of the product.
– **Stage-3 Build:** The Stage-3 build is the final build before production. This build should consist of only tooled parts to use as a final check before production.

As the time-line progresses and development gets closer to the final design of the product, the fidelity of the prototypes increase. AP_1 described the need for prototypes to be of the highest possible fidelity at any point in time. This allows for the largest amount of tests and learning from the prototypes. The first prototype may be a paper mock-up to get a visual representation of the design. Then, as the design is refined, higher fidelity prototypes allow more details to be tested and validated.

AP_3, the development manager, also described his own philosophy regarding the use of prototyping. For a given project, a list of risks is created and prioritized. The most important risks need to be addressed first and then the next important risk is addressed. These risks are addressed through prototyping and testing. Designs are tested and once they pass a given test, the corresponding risk is removed and the list is re-evaluated.

Table 2 shows a summary of the number of prototypes placed into each category of the taxonomies. All five of the conceptual related taxons have interview evidence relating prototyping to conceptual design activities.

Table 2 Summary of the Prototypes Discussed at Appliance OEM

			Interviewee			
			AP_1	AP_2	AP_3	Total
Number of Prototypes			5	7	2	14
HMP	Variety	Physical	5	7	2	14
		Non-Physical	0	0	0	0
	Complexity	System	0	2	0	2
		Sub-System	3	1	1	5
		Component	2	4	1	7
	Fidelity	Realistic	0	2	1	3
		Detailed	1	2	0	3
		Basic	3	1	1	5
		Form	1	2	0	3
Roles	Learning	Performance	4	5	2	11
		Unknowns	5	2	2	9
	Communication	Functionality	2	2	0	4
		Configuration	0	0	0	0
		Visual/Tactile	1	4	0	5
	Integration	Assembly	2	1	0	3
		Refine Function	2	0	0	2
		Refine Process	0	0	2	2
	Demonstration	Customer Demand	2	2	0	4
		Milestones	3	0	2	5
Design Needs	Experimental	Analytical Development	0	2	0	2
		Evaluation	5	6	2	13
	Validation	Proof of Concept	3	0	1	4
		Proof of Product	1	3	1	5
		Proof of Procedure	0	0	1	1
	Selection	Aesthetic	0	2	0	2
		Conceptual Level	4	0	1	5
	Interrogation	Configure System	2	0	0	2
		Optimize	0	1	1	2

The prototypes discussed at Appliance OEM were all physical in nature and the engineers more often prototyped components and sub-systems than complete systems. Due to the architecture of most appliances, individual components can be prototyped and their design iterated quickly, with a few complete system builds to ensure the system works as a whole. The prototypes filled many roles in communication, integration, and demonstration, but most often filled a learning role as well. These learning roles supported experimental design needs by often being used to evaluate properties or support analytical models.

From quick mock-ups using wood or cardboard to functional rapid prototyped parts, the engineers at Appliance OEM discussed the benefits or prototyping quickly and efficiently to learn and improve the design. Additionally, the practice of producing multiple concepts simultaneously and comparing them was mentioned several times. AP_1 described the following of "parallel paths" by building a large number of prototypes early on in the design process. This allows the designers to compare multiple solutions and evaluate them quickly.

When describing the effectiveness of prototyping early and often in the design process, AP_3 discussed how the process of building a prototype. Regarding one project, he mentioned: "Engineers…want to draw it out. They're working with CAD designers, and they're massaging it, working through it, and they put their first prototype together and it doesn't work." Alternatively, when prototyping, he said: "…we've put the first one together and the first thing you want to do is make changes. Before it's even built, you can see where you need to make improvements." The benefit of this is that it helps to illuminate issues as early as possible in the design process as well as identify new concepts. The prototypes can inspiration the engineer, prompting new ideas rather than just being a tool for making iterative changes to a design.

One interesting discussion covered a prototype that was used to mimic a problem. AP_1 described an unexplained issue that was occurring with water dispensers. The first step in finding a solution was to find the root cause of the problem. This was done by building a test system to mimic not only the water dispenser system, but also the installation process of the system and the environmental changes that would be seen during and after installation of the appliance. Using this prototype of the *problem*, AP_1 was able to determine the cause of the issue and work could begin on the solution. This could be classified as a divergent prototyping activity as it is aimed with defining the problem and opening up the design space for that problem. This example identifies a potentially new role for prototypes in the design process: prototyping for problem understanding.

4 CASE COMPARISON

When comparing to the practices of the two companies, it can be seen how the type of product can influence the approach to prototyping. At Automotive Supplier, where interactions between components are complex and hard to predict or model, system level prototypes are used for learning and evaluation. Additionally, some low fidelity component prototypes are used, but there are few instances of sub-system level prototypes. Much of this likely results from the maturity of the technology and the stability of the product offerings. In contrast, at Appliance OEM, component and sub-system prototypes can be made inexpensively using rapid prototyping technologies and provide learning or evaluation value. Complete system prototypes are still constructed as a formal part of the development process. It is also interesting to note that instead of approaching prototyping as a risky and expensive, the product development manager uses prototypes to specifically mitigate risks in the product design.

Both companies have found ways to successfully integrate prototyping into their development process and use prototypes in conceptual design. Observed practices form a set of guidelines for the use of prototypes in conceptual design. Further rigorous experimentation will help to understand the benefits, drawbacks, correct implementation of these guidelines.

- Plan for the purpose of the prototype.
- Prepare a path forward that is dependent on the possible prototype testing outcomes.
- Start out as fast and inexpensive as possible.
- Build as accurately as possible or is needed to answer what you need to know.
- Build prototypes that can perform double duty.
- Share resources between prototypes to build concepts to evaluate more of the design space.
- Following a systematic method for building prototypes can help manage costs and risks.
- Prototype early and often, then iterate.

Additionally, the interviews show that an engineer working on concepts further away from market launch of a product was more likely to build lower fidelity prototypes that are used for experimentation and learning. Conversely, an engineer working closer to the product launch is more likely to build higher fidelity prototypes for communication as well as learning.

5 CONCLUSIONS: HOW ARE PROTOTYPES USED DURING CONCEPTUAL DESIGN IN INDUSTRY?

Six interviews were conducted at two different companies in order to help understand how prototypes are used by industry during the conceptual design phases of a product development process. All of the prototypes discussed were classified according to the Hierarchical Morphological Prototyping taxonomy. The roles fulfilled and the design needs addressed by each prototype were also recorded. Overall, this research shows that prototypes *are* being used in conceptual design, even though there are literature sources advising against it. There is evidence in both companies that conceptual design activities are supported by prototypes, but the level of detail varies enormously. Moreover, the role that prototyping plays seems to be primarily related to testing and uncovering unknown issues. Based on the interviews and prototype classifications, there are several key takeaways.

- **Prototyping the problem:** Through prototyping a design problem, an engineer at Appliance OEM was able to better understand design issues and helped lead to the design of a solution.
- **Idea Stimulation role of prototypes:** Situations were described in the interviews where prototyping led to the refinement of a design as well as the creation of a new concept. This is a potentially new prototyping role that warrants further research in order to understand how prototyping can aid idea generation.
- **Evidence of prototyping culture used to mitigate risk, rather than being risky itself:** An interesting theme present in the interviews is that prototyping efficiently, keeping down costs while maximizing utility, is actually a core aspect of the two companies' development processes. Rather than seeing prototypes as a risk, they are a major tool used in mitigating the risks in the development process.
- **Value in prototyping process**: Not only were the prototypes used in their physical form, the process of *creating* a prototype proved valuable in some instances. A quote from the Appliance OEM highlights when describing how engineers have changes in mind before they are even finished with building their prototype. This is an idea that warrants further research to understand how it can be used to aid the development process.

While this case study does not provide definitive proof that prototyping in conceptual design holds a certain amount value, it does illustrate how it is viewed in industry. More importantly, a new, possible role for prototyping, idea stimulation, which can support the divergent, rather than traditionally convergent, activities in design, is identified. This role is the subject of a more detailed investigation in physical prototyping in ideation (Hess, 2012). The complete details of the case study and the interview transcripts are also available in (Hess, 2012).

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