

Student use of prototypes to engage stakeholders during design

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Introduction

Successful product design not only requires traditional design skills but also ongoing communication with stakeholders to gain critical insight into the intended products' objectives and stakeholders' real needs and wants^{1,2}.

But it can be difficult for stakeholders to articulate their needs and wants, especially when working across "cultures" (professional, geographic, technical) and disciplines³. It is the designer's responsibility to overcome these communication challenges in order to understand and define user requirements, which then can be transformed into engineering specifications essential for successful product design^{4,5}.

Experienced designers address these communication challenges through the use of prototypes. In addition to using prototypes in the traditional way, that is, to iterate and test an idea and to meet and verify design and engineering challenges, professional designers use prototypes throughout the development process^{1,4,5}. Prototypes help designers to frame the design problem and ask specific questions in order to gain valuable insight into stakeholders' needs³. In this way, designers' use of prototypes helps to facilitate a deeper understanding and knowledge of the problem.

In education, students often lack the background and are not provided with the necessary guidance for using expert prototyping techniques to maximize project outcomes^{6,7}. Today's engineering design curricula commonly view prototyping as a phase, a singular activity that occurs only once after performing engineering analysis⁸. This limited use may contribute to students' underutilization of prototypes. As a result, students may be missing out on the greater potential of prototypes that professional designers benefit from^{9,10}. This untapped potential cannot only have a negative impact on the creation of new products and services; it can also limit how universities prepare students for professional careers and competitiveness in today's economy.

An increased focus on engineering students' use of prototypes as tools for iteration and communication with stakeholders is warranted. In this study we investigate how students in capstone design courses currently leverage prototypes throughout the design process to engage with stakeholders, and we discuss possible implications for engineering pedagogy.

Background

Prototyping, a combination of methods that allows physical or visual form to be given to an idea, has long been recognized by professionals as an effective technique for product development^{4,5} and is often considered essential to the process^{11,12}. In *Serious Play*, Schrage argues "...prototyping is probably the single most pragmatic behavior the innovative firm can practice." He explains that beyond troubleshooting and problem solving, physical models provide a fundamentally different way of communicating around a "shared space" – the prototype. This, he continues, affects both internal and external communication and makes it easier for clients to articulate what they want by interacting with prototypes rather than articulating requirements.

Schrage compares this to restaurant patrons ordering a complete meal from a menu instead of singular ingredients, which would require more skill and insight than customers might possess⁵.

The use of design ethnography to develop a deep understanding of stakeholders' and end users' requirements has been shown to be helpful practice, especially in the early phases of a design project³. An advanced appreciation for stakeholder needs is essential when designing for intercultural (community, society, corporate, etc.) settings where designers often have limited knowledge about their targeted audiences⁴. However, eliciting and synthesizing sometimes-conflicting stakeholder information can be difficult for student designers^{12,13}, and can lead to superficial design changes that don't address underlying deficiencies¹⁴. To ensure the development of context-specific technologies that meet stakeholders' expectations and to improve product adoption, especially when communicating ideas across professional, geographical and/or cultural contexts, design processes must incorporate strategies to help designers more fully understand, and address, the intended products' objectives and stakeholders' real needs^{15,16}.

Problem scoping and information gathering are important competencies for engineering students to develop, but major differences exist between advanced engineering designers and students. In a study comparing design practices of expert and novice designers, Atman⁹ found that experts spent significantly more time on individual tasks and in each stage of engineering design. They invest more time scoping problems, gather more information and cover more categories like safety guidelines and budget.

Prototypes can also help to improve a design. Kordon¹⁷ argued that design errors can occur in a multitude of locations, both early and late in the process, but because of their potentially quick and cheap yet effective modeling nature, prototypes can serve the essential function of identifying design problems early. This allows for iterations and design improvements without the large investment of time and money that Viswanathan¹⁸ describes as "sunk cost." Many advocates suggest that prototypes should be created early and often and used iteratively throughout the product design process^{10,19,20}. Schrage suggests that "wasting' prototypes is essential... for detecting errors and discovering opportunities," "wasting" referring to the quick elimination of less promising approaches⁵.

Research Design

Study Purpose

As part of a larger study on the use of prototypes during design, our focus here was how students used prototypes to engage stakeholders. The study presented here was guided by the following research question: How and when do students use prototypes to engage with stakeholders throughout the design process? This research project was approved by a Midwestern university's Institutional Review Board.

Participants

A total of 16 students from three different engineering capstone design courses were interviewed for this study. Table 1 shows the distribution of students based on their gender, design course, and prior design experience. All student names were replaced by pseudonyms to ensure anonymity. Less than half of the students had not referenced previous design experience outside

of their capstone design project. Three students had higher education levels, having completed or were currently in a Master’s Program while three students previously completed an internship. The population was split evenly between female and male students.

Table 1: Student Participant Distributions

	Distribution of Participants		
Gender	8 Females		8 Males
Capstone Design Course	10 Mechanical	1 Biomedical	5 Multi-Disciplinary
On extracurricular project team?	YES – 6 students		NO – 10 students
Previous Internship?	YES – 3 students		NO – 13 students
Advanced Education?	YES – 3 students		NO – 13 students

Semi-structured interviews were conducted to gather information about the participants’ experiences during their semester-long capstone design course at a large Midwestern university. Students had either taken a mechanical engineering capstone, biomedical engineering capstone or multidisciplinary engineering capstone design course involving engineering, art, psychology, and business. All three capstone design courses required students to go through the entire design process starting with problem identification to analysis and finally validating a selected concept. All courses followed the typical engineering design process, had mandatory design reviews scheduled throughout the semester and a final report due at the end. Students were required to produce a model of their design for a final presentation of their project.

Protocol Development

A qualitative research approach was used for this study, and information was gathered from participants through a semi-structured interview format²¹. This approach provided guidance to the participants as they reflected on the entirety of their design project while allowing them the freedom to express their unique experiences and thoughts. Interview questions were designed to specifically follow the stages of the design process⁸ and, at times, to target detailed descriptions of the use of prototypes. These questions helped to elicit information about how the use of prototypes impacted the design process and how students learned from prototypes.

Interview question were developed iteratively. The research team reviewed and refined the questions several times during study development. A pilot study with four participants lead to further refinements and final iterations of the interview questions. The questions were then categorized to follow the engineering design process and organized according to their relevance to the use of prototypes. Below is an excerpt of the main question themes of the study with examples of actual interview questions. The same interview protocol was used with all participants. The semi-structured interview format enabled the interviewer to follow up on participant comments to extract additional information. Most follow-up questions were meant for clarification purposes or further elaboration on a particular comment.

Main Question Themes and Example Questions:

- Prototyping General:
What role did prototypes play with stakeholder interaction?
- User Requirements and Engineering Specifications:

What type of information did you think critical to get from stakeholders?
Were your stakeholders involved in this phase?

- **Brainstorming and Concept Development:**
Were your stakeholders involved in idea generation and concept development?
- **Evaluation and Concept Selection:**
Were your stakeholders involved in evaluating your concepts?
- **Engineering Analysis:**
Were your stakeholders involved in this phase?
- **Validation and Verification:**
Were your stakeholders involved in this phase?
- **Stakeholder Engagement:**
Who were the users and stakeholders in your project?
What role did prototypes play during stakeholder Interaction?
Would you have liked to have more, less or no stakeholder involvement?

Data Collection

Participating students were recruited through a mass email that advertised the study. The only prerequisite was that students had completed a capstone design class at the time of the interview. All participants were given a \$25.00 gift card for their contribution.

A member of the research team conducted all 16 interviews for the study over the course of six weeks. All participants gave their permission to have the interviews audio recorded for later data analysis. At the beginning of the interviews, students were asked for their definition of a prototype. Then, the interviewer defined prototypes for the context of the study to ensure a common definition. Here, we defined prototypes as “three-dimensional physical models, CAD models or two-dimensional sketches or representations that communicate an idea or a design concept.” Following that, students were presented with a diagram of the typical stages of the engineering design process⁸ and asked to indicate during which phases they used prototypes. The interviewer then proceeded to ask the interview questions and follow-ups when necessary.

Data Analysis

All recorded interviews were transcribed and re-examined by two editors for accuracy. An iterative, inductive coding approach^{22,23} was used to analyze the interviews through QSR NVivo 10, a qualitative coding software²⁴. The research team examined the transcripts and extracted quotes related to the guiding research question. Instead of imposing pre-existing categories that had been previously identified in other works, patterns and themes were allowed to emerge from the transcripts. The emergent themes went through multiple iterations as transcripts were coded and recoded by two members of the research team. After the themes were finalized, five interview transcripts were coded with the final categories to ensure a satisfactory inter-rater reliability level between the two coders. Categories and findings were developed based on the transcripts in their entirety.

Findings

Here we share the most frequently reported ways that students used prototypes to engage stakeholders. We summarize these uses of prototypes in Table 2 and describe the categories in more detail in the following sections.

Table 2: Findings

Code	Definition	# of Students (out of 16)	Example Quotes
Communicate Ideas	Used prototypes to share concepts and thoughts with stakeholders. This includes sketches, pictures, videos, and CAD models.	16	Some people didn't really understand, so you have to bring the physical model to see, to show what it looks like. With our engineering professor, the CAD was most helpful with him because he understood. The more physical things like the sketches on paper were more helpful with the doctors.
Gather Feedback on Design Ideas	Used prototypes to obtain assessments from stakeholders on the whole design or individual functions that can influence design decisions.	13	I think it's very helpful with the stakeholders because they have knowledge in their field. So they can use their knowledge...I can acquire their professional knowledge from their field and to adjust our product.
Demonstrate Form and Function	Used physical models to show stakeholders the shape and size of the selected concept as well as how the concept works	13	I think that was like really beneficial for them just to see what we were thinking and to see what we were trying to come up with and if it was similar to something they had seen before or completely new.
Define Problem	Used prototypes with stakeholder for understanding the problem that will focus and guide the entirety of the project.	10	We talked about ... existing products with the doctors. They often would talk about existing products because there are a lot of things that do exist to address some of the challenges that we identified that they just don't have.
Evaluate Human Factors	Gave prototypes to stakeholders to evaluate interaction with the design (ergonomics or human factors) such as the evaluation of size, comfort, weight, appeal of a layout, etc.	9	We wanted to do observations to see how people interacted with the physical object, what they did. Maybe they didn't say something, but the way that they picked up the object, the way that they found the feature...

Communicate Ideas

Students most frequently reported using prototypes with stakeholders for the communication of ideas. All 16 students mentioned at least once that they used prototypes to share concepts and ideas with stakeholders. The prototypes used included sketches, pictures, videos, and CAD models and were mentioned 49 times. Some students found that communicating their ideas to stakeholders with prototypes ensured that stakeholders understood the concept and that different prototypes were more helpful with a particular group of stakeholders. Student 7 explained:

“Some people didn't really understand, so you have to bring the physical model to see, to show what it looks like. With our engineering professor, the CAD was most helpful with him because he understood. The more physical things like the sketches on paper were more helpful with the doctors.”

Not only were prototypes helpful for clear communication, but the more frequently students used prototypes, the better their conversation with stakeholders became as student 12 described:

“The more we showed them a prototype, the better our conversation was. ... The more prototypes we brought with, the better the conversation was.”

Students also referred to prototypes as a unique form of communication tool that allows designers and stakeholders to understand ideas in new or different ways. Not only do prototypes ensure an exact understanding of a concept, the interactive component of the physical prototype provided a more comprehensive understanding beyond a verbal description. Student 11 quoted:

“To me, it's a method of being able to be on the same page about a particular concept that's in my mind that I want to convey to you as exactly as I'm thinking about it or as close to it as possible in your mind in some sort of a visual sense. I think for the user, it also served as a way to enhance communication to us because they had something physical that they could move around and show in some way or another.”

Gather Feedback on Design Ideas

Students frequently used prototypes to gather feedback on their design ideas from their stakeholders. Thirteen students said 56 times that they used prototypes to obtain assessments from stakeholders on the whole design or individual functions that then influenced design decisions. Although the function of gathering feedback is similar to that of communicating ideas, gathering feedback is an additional step that required more stakeholder involvement. Here, stakeholders not only reviewed but commented on the prototypes, which provided students with new information and/or led to changes in ideas. Student 2 described this experience:

“Prototypes were big in allowing us to communicate our ideas with the professors and show where we were going. Then we could have some back and forth and talk about our ideas and make tweaks”

The models also allowed students to gather expert insight into an area where they had little to no experience as student 1 explained:

“I think it's very helpful with the stakeholders because they have knowledge in their field. So they can use their knowledge... I can acquire their professional knowledge from their field and to adjust our product.”

Students found that different kinds of prototypes were helpful when gathering feedback from stakeholders. For many students, sketches emerged earlier in the process and were followed by physical models later. As this student 7 mentioned, physical models allowed stakeholders to

provide feedback that led to design changes, whereas sketches were used primarily for early feedback on the feasibility of an idea:

“When we showed our physical models to doctors they gave us feedback, and we were able to use the feedback to make changes. Even prior to using the physical models, though, we did show some doctors our sketches, and they were also able to tell us, “Maybe, I think this won't work; maybe this will work.” Getting that feedback was helpful, too. It wasn't just the physical models that we got feedback from.”

Demonstrate Form and Function

The use of prototypes to demonstrate form and function to stakeholders was described by 13 out of 16 students who mentioned this 23 times. For student 9 this was particularly helpful when their concept was only vaguely defined and, therefore, conveying the idea to stakeholders was challenging. Having a physical prototype allowed student 9 to communicate their thoughts and enabled the stakeholders to relate the idea to objects they were already familiar with:

“I think that was like really beneficial for them just to see what we were thinking and to see what we were trying to come up with and if it was similar to something they had seen before or completely new. It gave them a different way of thinking about it, grasping our idea that we were trying to communicate.”

Students found explaining functional aspects of their design challenging. Putting a physical representation of their idea into the hands of their stakeholders didn't only help to explain; it also enabled the stakeholders to provide feedback on the design. This highlights the communication issues mentioned earlier, where the describing of a functional aspect might be easy for an engineer but challenging for others to understand. Student 7 explained:

“Some people didn't really understand, so you have to bring the physical model to see, to show what it looks like. So, for them, being able to play around with the physical model and say, “Oh, this is how it goes together. This is how it's going to work,” they can provide very specific details and feedback for you.”

Define the Problem

Ten out of 16 students described using prototypes during problem definition. Student 9 who worked on a medical device with stakeholders in resource-limited settings found being able to refer to existing, familiar products was helpful, even though those products weren't available in the stakeholders' particular setting:

“We talked about ... existing products with the doctors. They often would talk about existing products because there are a lot of things that do exist to address some of the challenges that we identified that they just don't have. That was why, I think, they referred to existing products a lot because a lot of the doctors knew that there were things that they just didn't have.”

Using existing products as a form of prototypes helped the designers understand a problem challenge: In one case, the stakeholder provided existing products to help the students learn

about the problem. Student 5 used the existing products to identify areas they could improve on and that would make the new product more likely to be used:

“Just defining the problem was cool because you could see what the product was going to be used for and what there was already in place and just how to improve that and make it nicer and easier to use and make more people want to use it.”

Evaluate Human Factors

Prototypes were also used by students to evaluate human factors. Nine out of 16 students mentioned 27 times that they used prototypes for this task. The following quote from student 11 indicates how one team used prototypes, in this case existing products, early on in the process. In addition to asking specific questions, students were interested in learning from their end user by observing their actions:

“We wanted to do observations to see how people interacted with the physical object, what they did. Maybe they didn't say something, but the way that they picked up the object, the way that they found the feature...”

Another team employed prototypes for a human factor evaluation later in the process, when they had a functional prototype of their concept. Student 7 describes how the prototype was used to benchmark ease of use and performance of a new idea and how doctors, the intended end users, performed compared to students who were involved in the development process:

“One thing we did measure was how easy it was to put together these items and use the thing. We identified how long it usually took doctors to use the [new] method. We compared that time to the amount of time it took for students to put this together and implement it.”

Despite many students citing the usefulness of prototypes in their interaction with stakeholders, six students reported they did not use prototypes to interact with stakeholders. This is due to a number of reasons. First, students said they didn't have access to a particular stakeholder group like their end-user. Second, during the actual design project, students did not think to use prototypes in a certain way to engage with stakeholders. However, in retrospect, reflecting on their experience during the interview, a student from the same group stated ways they would have liked to have used prototypes with stakeholders. The quote of student 6 reflects this missed opportunity:

“Then they [could] tell us “No, you totally misinterpreted what I was thinking there.” That would be cool. We didn't get any of that feedback.”

Discussion

When asked early in the interviews about the use of prototypes, students most frequently stated that prototypes are used to demonstrate form and function and for testing purposes. When analyzing the frequency of actual prototype use during their projects, all students reported having used prototypes for testing and validating, and a majority (13 students) also used prototypes to demonstrate form and function to their stakeholders, in other words, as a communications tool.

Here, students' general perception of prototype use and their actual use during the project matched.

Only three students indicated at the beginning of the interviews that they thought prototypes are used for communication purposes. However, all 16 students said they used prototypes during the design process to engage with stakeholders as well as to communicate with their team members. This is particularly interesting since even though students had just experienced the values prototypes can provide in real design projects, they didn't mention this when giving their initial definitions of what prototypes are used for to the interviewer. Multiple successful projects might be necessary to ensure that these experiences translate into retained learning and knowledge²⁰.

When reflecting on how they used prototypes with stakeholders to communicate their ideas, gather feedback and demonstrate form and function, students realized that they didn't use prototypes to their fullest potential. This underlines discrepancies found between students' use of prototypes and best practices employed by expert designers. In *Biodesign: The Process of Innovating Medical Technologies*, Yock et al. encourages the iterative use of prototypes to refine a selected concept until the underlying need of the user is ultimately solved. This proposed approach is highly iterative as each prototype builds on what has been learned from the previous model, yet students in our study rarely used prototypes during these early phases or even iteratively²¹.

Atman⁹ has shown that novices tend to spend less time in each stage of engineering design and gather less information to scope a problem, specify user requirements and engineering specifications than experienced designers. The front-end phases of design – those focused on problem definition – can be particularly challenging for novice designers. For example, student participants in our study cited developing user requirements and translating them into engineering specifications as some of the most difficult design activities performed during their capstone course.

As de Beer² discussed, functional prototypes are more easily understood and accessible than virtual descriptions and can help to engage with stakeholders. Prototypes can facilitate iterative communication among designers, engineers and stakeholders. In our study, students found that their prototypes improved communication and enabled a more active participation of the stakeholders in the design process and ultimately led to better project outcomes¹³.

Limitations

This study focused on engineering design students from a large Midwestern university. The participants in the study were limited to students from only three disciplines within a single university and the findings might not be representative of other courses, disciplines, universities, students, etc. Furthermore, participants described how they used prototypes during their projects, but we have no evidence for whether or not they actually used prototypes the way they said they did. Some of the students worked on projects for resource-limited settings that might have added intercultural challenges, which not all participants experienced.

Educational Implications

Based on the findings of this study, as well as research mentioned earlier, students might benefit from an increased use of prototypes in their projects. Engineering education curricula currently view prototyping as a one-time activity that typically occurs when testing and validating a selected concept. Student engineering designers are frequently reminded not to prototype until they have, in theory, proven and verified their design. This approach may be helpful in reducing the sunk cost (time and resources) invested in a model that does not represent the final solution, however, it deprives student designers of valuable opportunities to engage with stakeholders and improve the design^{15,18}.

To help students use prototypes more effectively, an instructor might ask students to actively engage with stakeholders with the assistance of prototypes during several phases of the project. This could materialize in the form of individual phase deliverables or a restructured course outline in which prototypes, likely of increasing fidelity, become a more integral and integrated part of the design process. Design researchers might use these findings to broaden our understanding of the impact prototypes have when engaging with users and stakeholders. Through this we can develop strategies that maximize prototypes' potential to improve communication between designers and stakeholders and to improve the overall project outcome.

Conclusion

This paper explored how and when students used prototypes to engage with stakeholders throughout capstone design courses. Most of the reported activities related to how and when students used prototypes with stakeholders in beneficial ways contrast with current engineering design curricula, in which prototypes are required to be built only during a designated phase for testing and validation purposes. This practice imposes drastic limitations on the iterative use of prototypes that experienced designers use to improve design ideas. It also deprives students of the opportunity to use prototypes as communication tools and gain cultural and social insights that might lead to a better understanding of stakeholder needs and wants. This is especially critical when designing across cultures and disciplines with stakeholders from different professional, technical, socioeconomic, geographic, etc. backgrounds. Here, the increased use of prototypes can help to break down communication barriers and eliminate the negative impact of ill-defined problems on the successful adoption of products and services. With this understanding we can begin to rethink how we prepare future engineering designers for professional practice through engaged project learning and provide them with the tools necessary to become well-rounded, empathic designers.

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