



Effects of a Structured Prototyping Strategy on Capstone Design Projects

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Prototyping is often a very important phase in a capstone design project. However, in many cases, prototyping decisions are made arbitrarily by students, adversely affecting the quality of the final product delivered. At The University of Texas at Austin we are developing a structured prototyping strategy tool based on a synthesis of prototyping techniques that have been shown to be effective. Our strategy tool leads designers through the process of making decisions about aspects of a prototype program, such as how many concepts to prototype, the number of prototype iterations to complete for a given concept, and whether to use scaled prototypes. In this study we evaluate whether explicit discussion of these prototyping decisions affects the results of the capstone design projects. The goal was to determine if exposure to the prototyping strategy tool leads to an increase in the number of prototypes constructed, as research suggests that early and frequent prototyping leads to increases in the quality and the novelty of designs. At the beginning of the semester, students in the capstone course received instruction on the benefits of prototyping and on the use of prototyping strategy tool. We then conducted interviews at the end of the semester to evaluate the students' prototyping efforts. These results were compared to previous capstone projects where the students did not receive formal guidance on making prototyping decisions. The results of the comparison show statistically significant increases in the proportion of teams opting to create prototypes and the average number of prototypes per team. This paper describes the study in detail, analyzes the results, and presents conclusions and future directions of the research.

Introduction

Prototyping is one of the most important phases of an engineering design project. Prototyping is the process of generating a pre-production manifestation of a design concept during the stages of concept generation and design verification. However, in spite of its high importance, the process of prototyping is often not implemented in a structured manner in capstone design projects. In some capstone courses, students finalize their design concepts with little to no physical validation. Several research studies in the field of capstone design indicate that student design projects would benefit highly from physical prototyping to prove the feasibility of their concepts.^{10, 11, 12}

A research group at The University of Texas at Austin is developing a systematic prototyping strategy that leads designers through the important prototyping decisions¹⁴. In the past year, this prototyping strategy tool was presented to students in the capstone design class in mechanical engineering in a structured manner. The chief goal of this study was to identify the effects, if any, of this exposure on structured prototyping decision-making in terms of the number and nature of prototypes constructed.

Background and Literature Review

Prototyping can be understood to mean the development or testing of a new design concept to iteratively improve the product before the final design and the onset of manufacture. As mentioned, earlier prototyping is often very crucial to the success of a design project. Moe et al.⁹ state that 40-60% of product development resources are spent on products that are cancelled or do not yield adequate returns. Furthermore, they argue that effective prototyping decisions (e.g., how many concepts to prototype simultaneously, how many iterations to pursue for a particular design concept) are critical aspects of a product development process and its success. Simulating a process through prototyping can reduce risk without committing the time and cost of full production⁴. Prototyping is an effective way of comparing design alternatives and aiding in concept selection⁵. Prototypes provide feedback on evolving designs. Prototypes can also serve as efficient tools to communicate design intent to non-technical audiences. In addition the process of constructing and refining a 3-D physical prototype can uncover design issues in a way that alternative representations often cannot⁴. Research conducted to investigate the relative importance of different product development cycles has shown that prototyping plays a key role in determining the outcome¹. One study³ of U.S. Department of Defense (DoD) design projects over a 40 year period lists the following benefits of prototyping: (2) reduced technical risk; (2) validated designs; (3) evaluated manufacturing process; and (4) refined design requirements.

Because of the benefits obtained from physical prototyping many researchers encourage prototype building in engineering design projects. Tom Kelley⁷ of IDEO recommends that prototypes should be regularly used throughout the product development process. Some researchers encourage the use of prototypes in the early stages of the design. For example, McKim⁸ suggests that building physical models encourages the visualization of problems in complex systems. Also, he states that externalizing ideas using physical models helps designers to minimize risk associated with the initial assumptions of the design process regarding features and functions of the product. Vishwanathan conducted an in-depth study of graduate design students to identify the beneficial practices of prototyping⁶. The heuristics suggested by this study include “use standardized parts”, “support model building with analytical calculations” and “avoid detailing early prototypes to reduce the effects of sunk cost”.⁶ Also the DoD study³ suggests the following best practices for successful prototyping:

1. Prototypes should aim to test key design attributes associated with the highest level of uncertainty.
2. Prototyping effort should only focus on the minimum necessary requirements specified.
3. During the prototyping stage there should be no commitment to production.
4. Once the prototyping process is underway, no design requirement or performance expectation should be added to the design objective.

Several research studies justify the increase in the number of physical prototypes as one important variable in judging the success of a capstone design project. This is, in part, due to the

fact that prototyping aids the designer in verifying that the design requirements for a project have actually been met; which many would say is the ultimate measure of a design's success. In addition, prototyping has been shown to increase the novelty of design outcomes. For example, Youmans¹³ concluded that physical prototyping plays an important role in the reduction of design fixation. The study suggests that physical interaction with the materials improved originality and functionality of the user's design. Vishwanathan and Linsey¹⁰ reached a similar conclusion in a study of the causes of design fixation and methods to reduce it. Kiriyama and Yamamoto¹¹ concluded that physical prototyping and testing contributes most to the acquisition of knowledge while designing new products. Yang and Epstein⁴ concluded that iterative physical prototyping results in performance improvement due to refinements of the previous models. Zemke¹² discusses implementing a cycle that forces students to construct more than one prototype. He observes that building prototypes reinforces conceptual understanding and leads to more feasible designs. He suggests the use of multiple prototypes as shortcomings in design concepts are not immediately apparent without physical prototype validation. He encourages the liberal use of physical prototypes to assist designers in addressing complex issues and delivering the best possible project deliverables.

Prototype Strategy Development Tool

Our prototyping strategy tool was developed by assimilating successful prototyping heuristics and practices. The goal is to provide design teams with a systematic approach to developing a planned prototyping strategy. The tool leads designers through six main prototyping strategy decisions:

1. How many concepts should be prototyped in parallel?
2. How many iterations of each concept should be built?
3. Should the prototype be virtual or physical?
4. Should subsystems be isolated?
5. Should the prototype be scaled?
6. Should the design requirements be temporarily relaxed?

The prototyping strategy tool is shown in Figure 1. Definitions of the key variables are given below.

Number of concepts to prototype in parallel. Research studies have shown that when design teams pursue multiple concepts in parallel there is an increase in performance of the final prototype. The tool uses a decision matrix and Likert scales to help designers determine if the resources (time, budget) are available to prototype multiple concepts, and if the performance requirements warrant the effort. If the answers to the questions suggest that it is preferable to pursue multiple concepts then teams must decide how many concepts to prototype in parallel and which concepts they will pursue.

Numbers of iterations. Research shows that conducting multiple built-test-redesign cycles on a given design concept improves the ultimate performance of the product. Again, Likert scale answers in a decisions matrix helps designers determine if resources and requirements allow multiple iterations. This process is repeated for each concept identified as a candidate for prototyping.

Virtual vs. physical models. A physical prototype is a tangible, material model of a product or subsystem, while a virtual prototype is a computer-based model (CAD model, motion analysis, FEA, CFD, etc.) of a product (e.g. architectural CAD models of skyscrapers). Virtual prototypes may suffer from fidelity issues, but can be easily changed to explore alternative designs. Physical prototypes exhibit accurate behavior (comparatively), but must be reconstructed to explore alternatives.

Subsystem Isolation. The different subsystems can be isolated, prototyped and tested separately when sufficient information is available to isolate the subsystems. Also subsystem isolation can be beneficial if any particular subsystem requires greater consideration in terms of prototyping resources compared to the other subsystems.

Scaling. When a full system model is very costly or impractical to prototype to scale, building a scaled prototype is an effective way to test the system⁶. The prototype strategy tool guides designers for a single iteration in the prototyping process. They are advised to use the prototyping strategy guide again for future iterations

Relaxation of design requirements. Prototypes may be built with “relaxed” design requirements to simplify the process (e.g. an engine that runs at partial torque values to initially reduce major damping modes in engine block design).

Compute the average response to the prompts under each category to determine strategy.

		Strongly Disagree. -2	Disagree. -1	Neutral. 0	Agree. 1	Strongly Agree. 2
1	For a high avg, develop multiple concepts; else, build one only.	One Concept			Multiple Concepts	
a	There are sufficient materials to prototype multiple concepts.					
b	There is sufficient time to prototype multiple concepts.					
c	Rankings of several concepts are very close (e.g. from Pugh chart).					
2	For a high avg, iterate; else, build once.	Do Not Iterate			Iterate	
a	The difficulty of meeting the requirements will necessitate iteration.					
b	The difficulty of manufacturing will necessitate iterative prototyping.					
c	My team has minimal prototyping experience.					
3	For a high avg, use a virtual prototype; else, use physical models.	Physical			Virtual	
a	Virtual prototype(s) will require less time than a physical one(s).					
b	Virtual modeling will validate: physics, interfaces and/or requirements.					
c	A CAD model is needed for analysis (FEA, CFD, etc.) or manufacture.					
d	Time & budget allow pursuit of both virtual and physical prototypes.					
4	For a high avg, isolate subsystems.; else, integrate the system.	Integrate Subsystems			Isolate Subsystems	
a	Interfaces between subsystems are predictable and/or are NOT critical.					
b	1 or 2 subsystems embody critical design requirements & need iteration.					
c	A subsystem build would significantly reduce time, cost or complexity.					
d	An isolated subsystem can be properly tested.					
5	For a high avg, use a scaled model; else, use a full size model.	Do Not Scale			Scale	
a	Scaling law(s) will permit accurate system modeling via a scaled build.					
b	Scaling will significantly simplify the prototype.					
6	For a high avg, relax requirements.; else, pursue full requirements.	Do Not Relax			Relax Design Requirements	
a	Requirement flexibility allows significant results from a relaxed model.					
b	Requirement relaxation will significantly simplify the prototype.					

Figure 1: Likert-Scale matrices for determining the six prototyping strategy variables

Research Methodology

The efficacy of our prototyping strategy development tool was experimentally evaluated in the capstone design course in the Department of Mechanical Engineering at The University of Texas at Austin. Our capstone design program provides students the opportunity to apply engineering design methodology using analysis and synthesis to solve open ended projects funded by industrial sponsors. Some examples of previous projects included in this survey are “Design of a high temperature test setup”, “Design of a veterinary gurney”, “Design of a cam phaser for Formula SAE racecar”, “Analysis of swimmer’s block jump” and “Design of mobile mount for semi ruggedized notebooks”. These examples make it apparent that the capstone program consists of projects from a wide variety of industries including the oil and gas industry, biomedical industry and the automobile industry. When a prototype is required by the sponsors often the students create a high fidelity custom fabricated prototype, such as the one shown in Figure 2. However some sponsors do not require a prototype to be built as a part of the final deliverables. Hence it was particularly interesting to study the students’ desire to implement and learn from physical prototyping, even when it was not mandatory.



Figure 2: An example of a prototype built in the capstone design program: a cam phaser

Senior design teams of 3-4 mechanical engineering undergraduates complete their projects in one semester. The wide variation in the average level of difficulty and the scope of the projects makes this an important study to gauge the overall effectiveness of the prototyping strategy tool. As noted above, some project sponsors expect a working prototype as a deliverable, while a virtual CAD model of the intended design suffices for some projects. For projects requiring a working prototype, teams often build a single version and do not iteratively improve the prototype by testing and redesign. The key hypotheses to be tested by this study were:

1. Does exposure to the prototyping strategy tool lead teams to create more prototypes?

2. Because of exposure to the prototyping strategy tool, do teams who are not required to submit a prototype as a deliverable choose to make one nonetheless?

To answer these questions, we compared teams who were presented with the formal method of implementing a prototyping strategy tool, who served as the experimental group, and teams from courses in previous years, who served as the control group (because they were not exposed to the prototyping strategy tool). To gain information about the prototyping efforts of the teams in the control group, reports from previous capstone design projects were studied. Each report details each stage of the design project assigned to the team, including any physical prototyping during concept selection or concept development. While writing these project reports the students were reminded that they would not get any credit for any aspect of the project not described in the reports. Hence it is fairly safe to assume that if a project report does not mention physical prototypes then the team did no physical prototyping. The project reports detailed the use of physical prototypes fairly explicitly, so little interpretation is required by the reader. The reports were studied until an asymptomatic trend emerged with respect to the average number of prototypes implemented per team.

The students in the two most recent semesters of capstone design class served as the experimental group. The prototyping strategy guide was presented to each class early in the semester. The presentation was structured to educate students about implementing prototyping in a structured manner, emphasizing the benefits of prototyping if done correctly. The presentation discussed the situations in which prototyping, particularly physical prototyping, would be most beneficial. It also introduced students to some strategies to implement prototyping successfully such as requirement relaxation, scaling isolation etc. To provide the students with an efficient method to implement prototyping they were presented with our prototyping strategy tool. They were led through the use of Likert scales to guide in decision-making for prototyping with the help of an example. The sessions were fairly interactive and the students were encouraged to clarify any questions regarding the use of the strategy tool.

After presenting the integrated prototyping strategy guide, the students were encouraged to use this guide to aid them in making prototyping decisions in the context of their design projects. At the end of the semester the students submitted a survey after successful completion of their design projects. The students were asked to describe their prototyping experiences. The details of the number of prototypes built, types of prototypes and function of each prototype were captured by the survey. The survey also collected feedback regarding the prototyping strategy guide itself in an effort to improve it.

Results

This section discusses the results of our experiment to test the two hypotheses presented above. Quantitative results were analyzed using Student's t-test. We assumed that a p value of less than 0.05 is sufficient to reject the null hypothesis and accept the alternate hypothesis.

To test hypothesis 1, the reports from the control group were analyzed to determine the average number of prototypes created per team. The reports from the last six semesters prior to the beginning of the study were analyzed until an asymptomatic trend emerged with respect to the average number of prototypes made per team.

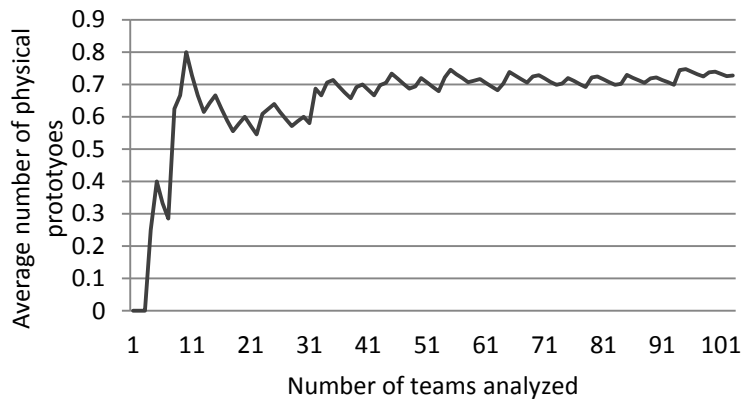


Figure 3: Average number of prototypes per team versus number of projects analyzed.

As shown in Figure 1, after analyzing about 100 project reports a clear asymptomatic trend emerged, approximately 0.7 prototypes per team. These results were compared with the 45 teams that were exposed to the prototyping strategy. Figure 4 compares the average number of physical prototypes per team reported by the experimental group compared to the analysis of the control group. The results show that on an average these teams made 1.66 physical prototypes per team. The increase in the number of physical prototypes was statistically significant with a p value of 0.008.

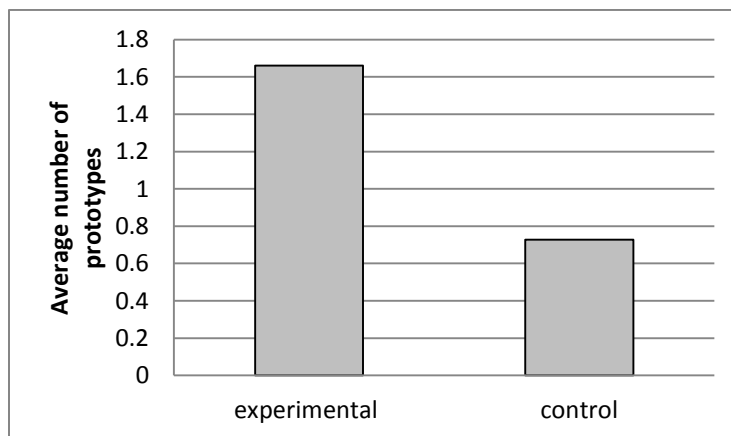


Figure 4: Comparison of average number of prototypes

An important goal of using this prototyping strategy is encouraging students to choose to build prototypes where appropriate as part of the design process, even in cases where a prototype is not required by the sponsor. To test this hypothesis, the projects in both the experimental and control groups were divided into subgroups based on their deliverables. We determined the proportion of teams opting to construct at least one physical prototype that was not required. The results are documented in Figure 5.

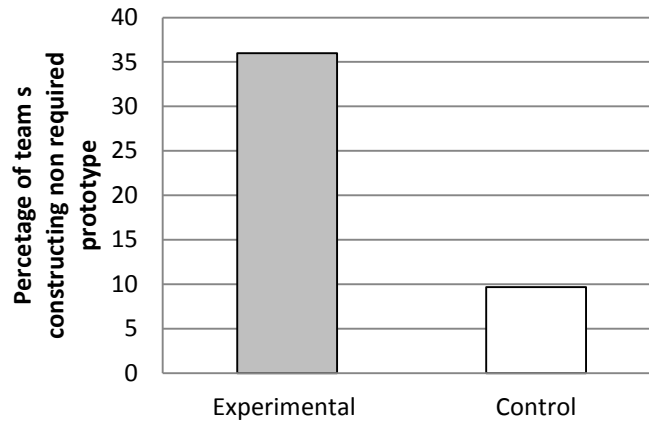


Figure 5: Comparison of proportion of teams opting to create non-required physical prototypes.

In the control group of previous design projects about 62 teams of those analyzed were not required to construct physical prototypes as a part of their final deliverables. Of these teams only 6 decided to build physical prototypes (about 10%). In the experimental group 25 teams were not required to build physical prototypes as part of the final deliverables. Of these, 10 chose to build physical prototypes (40%). This increase in the percentage of teams electing to construct physical prototypes was determined to be statistically significant with a p value of 0.0004.

Discussion

The first hypothesis was intended to gauge whether exposure to the prototyping tool would lead to the application of effective prototyping techniques by the designers. The exposure to the prototyping strategy led to a statistically significant increase in the average number of prototypes developed. We believe exposure to the prototyping strategy emphasized the importance of physical prototypes to the designers. The exposure to a systematic prototyping tool to organize prototyping effort encouraged the use of multiple prototypes.

With regards to the second hypothesis it was observed that the proportion of teams opting to make a physical prototype without being explicitly required to do also increased with a statistical significance after exposure to the prototyping strategy. This result also indicates that the positive effects of prototyping can motivate a team to pursue prototyping even when the project sponsor does not mandate physical embodiment of the product.

Limitations

A possible shortcoming of this study arises from the fact that the results are based on analysis of design projects in an academic domain. This makes generalizing the results difficult. However, as mentioned earlier, the capstone design program solicits projects from industry. The diversity in terms of both the types of industries sponsoring projects and the variety of the projects themselves offers some assurance that the results have implications beyond academia.

Also, in this study the number of prototypes constructed is used as a metric to assess whether exposure to the prototyping strategy tool has persuaded designers to think about these critical prototyping decisions. This approach was adopted based on several research studies^[3, 6, 7, 10-13]. However, future research can consider other metrics, such as percentage of teams opting to construct scaled prototypes, or opting to isolate subsystems in their prototypes, among others.

Future Research

Future work should focus on collecting data on other prototyping parameters such as subsystem isolation and prototype scaling. In the current research the students are just being exposed to the methods in a single presentation. Instead of just holding a single discussion on the benefits of prototyping, the importance of prototyping could become a topic of discussion in the regular interactions that the students have with their teaching assistants throughout the semester. It would be also be beneficial to seek better ways to assimilate prototyping methods into the pre-existing framework of design process. We also expect to improve the prototyping tool itself based on student feedback.

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