The Thesis Committee for Brock Usher Dunlap
Certifies that this is the approved version of the following thesis:

Active Learning Module Assessment and The Development and Testing of a New Prototyping Planning Tool

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

Richard H. Crawford

Daniel D. Jensen

Active Learning Module Assessment and
The Development and Testing of a New Prototyping Planning Tool

by

Brock Usher Dunlap, B.S.

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Dedication

This thesis is dedicated to my parents who have taught me the value of faith, education, and hard work; and to my wife who is my guiding light.

Acknowledgements

In my time as a graduate student I have had the privilege of working with several great professors and students. First and foremost, I would like to extend a special thanks to Dr. Richard Crawford who served as my graduate advisor here at The University of Texas at Austin. His wealth of insight and patience has guided me through my research and educational experience. I would also like to thank Dr. Dan Jensen at the United States Air Force Academy for playing a vital active role in both the Active Learning Module and Prototype Strategy research. Dr. Matthew Green joined us in our second year of the prototyping strategy development and was invaluable in his contributions. Through their interactions with me and other students, all three of these men have taught me that the value of those you work with is much greater than the work that needs to get done.

I am grateful for the National Science Foundation for providing funds for the development of Active Learning Modules. This important work is helping engineering students become better prepared to work in industry.

Finally, I would like to thank my fellow students who I have been privileged to work alongside through the years: Brad Camburn, Chris Hamon, Ella Sargent, and Jake Adams.

Abstract

Active Learning Module Assessment and The Development and Testing of a New Prototyping Planning Tool

Brock Usher Dunlap, M.S.E.

The University of Texas at Austin, 2014

Supervisor: Richard H. Crawford

This thesis contains the research findings from my participation in two research projects. The first is the development and assessment of Active Learning Modules (ALMs) for engineering students. The ALMs assist students in learning complex Finite Element Analysis (FEA) principles. We measure the effectiveness of the modules by issuing pre- and post-module quizzes and analyze the differences of the quiz scores. Active learning modules are used to meet the needs of all students' learning styles. Each student who uses an ALM takes a series of learning style assessment quizzes (MBTI, LIS …). We statistically compare the learning styles and quiz scores to ensure all learning styles are improving equally well. In cases where they are not, we created a tool to make suggestions to the ALM developer on how to adjust the ALM to meet the needs of the outlying learning style group(s). Following modification, the implementation and evaluation process of the ALM is repeated.

My second area of research focused on the development of a concise prototype strategy development tool. This tool guides engineering product development teams

through six critical prototype strategy choices: *(1) How many concepts should be prototyped? (2) How many iterations of a 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?* This list of choices is not comprehensive but served as a starting point for this groundbreaking research. The tool was tested at The University of Texas at Austin and the United States Air Force Academy. Results indicate the method did improve students' performance across a number of assessment metrics.

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CHAPTER 1: THESIS OVERVIEW

This thesis contains the research findings from my participation in two research projects and is broken into three major sections. The first section (Chapter 2) focuses on the development and assessment of Active Learning Modules (ALMs) for engineering students. The ALMs assist students in learning complex Finite Element Analysis (FEA) principles. We measure the effectiveness of the modules by issuing pre- and post-module quizzes and analyze the differences of the quiz scores. Active learning modules are used to meet the needs of all students' learning styles. Each student who uses an ALM takes a series of learning style assessment quizzes (MBTI, LIS …). We statistically compare the learning styles and quiz scores to ensure all learning styles are improving equally well. In cases where they are not, we created a tool to make suggestions to the ALM developer on how to adjust the ALM to meet the needs of the outlying learning style group(s). Following modification, the implementation and evaluation process of the ALM is repeated.

My second major section (Chapter 3) focuses on the development of a concise prototype strategy development tool. This tool guides engineering product development teams through six critical prototype strategy choices: *(1) How many concepts should be prototyped? (2) How many iterations of a 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?* This list of choices is not comprehensive but served as a starting point for this groundbreaking research. The tool was tested at The University of Texas at Austin and the United States Air Force Academy. Results indicate the method did improve students' performance across a number of assessment metrics.

The third section (Chapter 4) of this thesis is a continuation of the prototype strategy development. As outlined in Chapter 3, the guide was implemented in an academic setting with students working on either corporate sponsored projects or a controlled design experiment. To some this may only show that the prototype strategy guide is applicable only with in academia. To prove otherwise I have put together a research proposal to build a case for how this prototype strategy research is applicable within one of the fastest growing industries in the world: MEMs device development.

The goal of both the ALM and prototype strategy development research efforts is to improve engineering education. The tools and methods discussed here help solidify pertinent engineering concepts and give students hands on experience in prototyping methodology. This knowledge is applicable to a wide range of industries and will better prepare students to enter their careers.

CHAPTER 2: ACTIVE LEARNING MODULES

As technology and innovation continues to race forward and evolve, so too the techniques of educating tomorrow's engineers must change, adapt and grow to keep up. As an example, due to its precision and all-encompassing ability, finite element analysis is a practice that is being used more frequently in industry. Finite element theory is taught in universities but typically only at a graduate level; therefore, as engineers graduate with their bachelor's degrees they are ill-prepared to work in the capacity that companies need to fill. It is then left to companies to fill the void and train their new hires according to these fundamental practices.

On the other hand, engineering educators feel overwhelmed by the massive amount of material students need to know upon graduation. The curriculum is already overloaded with just the required classes. There is simply not enough time, faculty, or resources to expand the engineering course track. To alleviate this pain engineering education is turning to an 'active learning' style of teaching in which students take the responsibility for teaching themselves certain topics. In response to the need for more active learning in engineering curricula as well as to meet the need to introduce undergraduates to the finite element method, we have created, implemented and assessed a suite of Active Learning Modules (ALMs).

2.1. Background and Motivation

Active learning is an approach to teaching which invites students to engage with the material being taught through reading, writing, discussing, listening and reflecting. These actions lead the students to synthesize, evaluate, and understand the concepts. This approach is considered "active" because it contrasts from the traditional mode of teaching where the teacher lectures while the students listen passively. Research has proven that teaching engineering students with active learning techniques can improve students' aptitudes to learn [1]. Due to these advantages, active learning tools are becoming preferred by educators for addressing the struggles students face with complex engineering principles. This becomes especially trying for teachers as they must meet the needs of all backgrounds, demographics, and personality types [2].

One of the sole purposes of college education is to prepare students for success in their employment pursuits, whether they be commercial or academic. As technology advances, engineering tasks and the tools used to complete those tasks become more complex. This creates a challenge for educators because it becomes increasingly difficult to stay up to date with these technological advances. When educators fall behind the technology advancement curve students then leave their undergraduate experiences ill-prepared to meet the needs of future employment.

One such advanced technique that exemplifies this predicament is finite element analysis (FEA). The finite element analysis method is widely used in engineering practice. FEA is a numerical technique used for approximating solutions to complex differential equations. Example engineering applications where solving differential equations is pertinent include: modeling of mechanical vibrations, heat transfer analysis, structural fatigue analysis, computational fluid dynamics, etc. Various FEA tools have been built to aid engineers in performing these complex analyses and they are widely used throughout industry because they shorten product development cycles [3, 4, 5]. In the past, due to the intensive underlying mathematical theory, FEA methods were generally taught to graduate students. In recent years, however, engineering firms are asking for BS graduates to be able to apply this complex analysis technique [3,5]. Unfortunately in many engineering undergraduate programs, FEA is not a part of the required curriculum and therefore graduates lack the knowledge necessary to use the tools in industry.

In contrast to the past, these tools are increasingly being used by BS engineering graduates and even technicians. Although they may not have an understanding of the underlying theories upon which these tools are based, they can be taught to effectively use the tools and interpret the results.

Steif (2004) recognizes that there have been many efforts to incorporate these tools into undergraduate learning. These efforts tend to follow two schools of thought. The first teaches students to use commercial FEA packages and compares the results with other analysis methods. The second approach strives to introduce students to the underlying numerical methods. Although these approaches each have their advantages, they appeal differently to each department and instructor. For instance, many engineering departments feel the overhead of teaching software user interfaces is cumbersome and detracts from time being spent on potentially more important topics [6]. The 2012-2013 Accreditation Board for Engineering and Technology, Inc. (ABET, Inc.) Criteria for Engineering Programs dictate that engineering programs must equip their engineering students with "an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice" [7, Criterion 3 (k)].

A team or researchers led by Brown at the University of the Pacific has developed a suite of active learning modules to overcome the classroom struggles of teaching FEA methods [8]. The main goal of our work is to educate a group of diverse undergraduates with a basic understanding of FE theory along with practical experience in using commercial FE software to solve engineering problems. Despite the students' differing learning styles, personality types, and demographics, we want the learning modules to be effective for all students. To address all these factors for each student we have used the Kolb Learning Cycle as our pedagogical foundation for this research project.

2.1.1 Kolb Learning Cycle

David Kolb, a pioneer in experiential learning, concluded learning is the process of creating knowledge through experience [9]. Learning through experiential encounters requires active participation on behalf of the student, as opposed to the typical passive engagement resulting from teacher-led instruction [10]. Based upon these ideas Kolb created the Experiential Learning Cycle. As displayed in Figure 1, the process of learning takes place through four stages: reflective observation, abstract conceptualization, active experimentation, and concrete experience. These learning experiences result in two pairs of variables: feeling vs. thinking and doing vs. watching. According to Kolb each individual has a preferred learning style, but all students respond to all the learning styles and to some degree need to experience all of them [11].

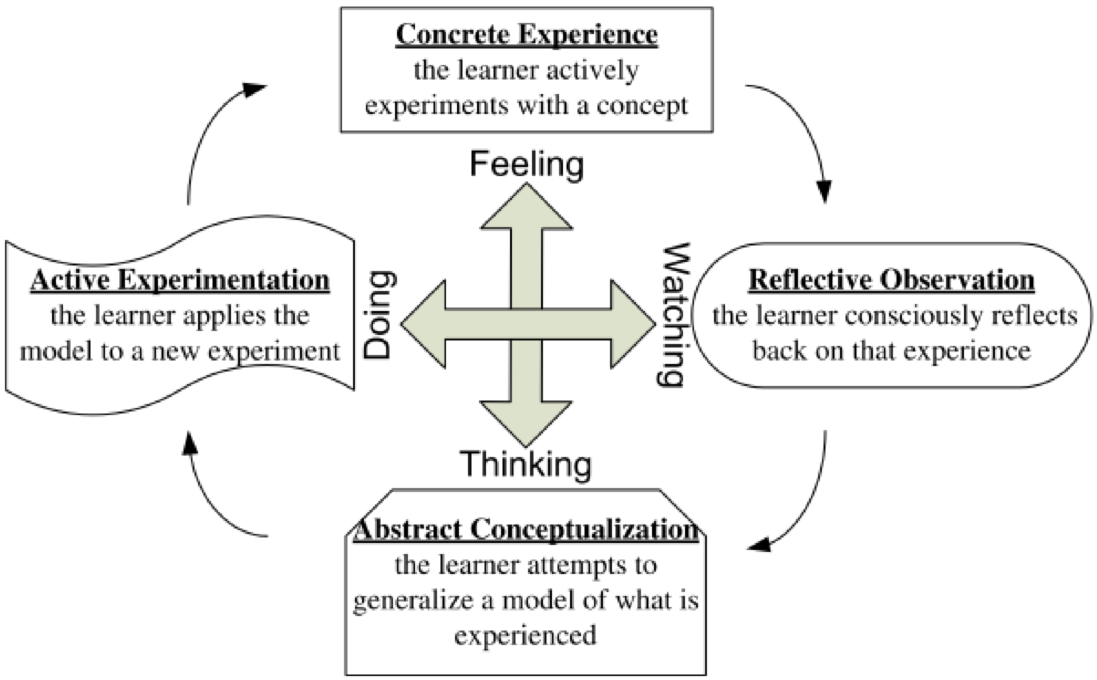


Figure 1. Four stages of the Kolb's Experiential Learning Cycle [9].

Brown et al., have leveraged the Kolb Learning Cycle to improve students retention of the complex procedures involved in FE analysis [[8]]. The students are first introduced to FEA theory during their traditional course lectures. Professors discuss the background of FEA, fundamental mathematics, the topology of the various finite elements, error analysis of FEA results, and how to model engineering problems using this technique. The students then practice these principles discussed by working through the FEA learning module. The learning module guides the students step-by-step through the process of building a FEA model for a specific real world engineering problem and then solving the problem.

2.1.2 LEARNING STYLES

As mentioned previously, everyone tends to have one main mode of learning that is most effective. In order to be effective for all students, each FE learning module developed in this research is designed to appeal to all learning styles. The Felder-Soloman Index of Learning Styles contains four dimensions of learning: active/reflective, sensing/intuitive, visual/verbal, and sequential/global.

The first preference pair, active/reflective, deals with how information is processed. “Active” learners retain information by discussing it with others, whereas “reflective” learners prefer to internalize the information first. The second learning style preference pair, sensing/intuitive, considers how students take in information. Students who are “sensing” learners enjoy connecting information to real world applications. On the other hand students who are “intuitive” learners like to discover new relationships and theories. The third learning style preference pair is visual/verbal. “Visual” learners remember what they see (ie. pictures, diagrams, etc.) whereas; “verbal” learners prefer written or spoken explanations. The fourth learning style preference pair is sequential/global. “Sequential” learners gain understanding linearly through logical steps. In contrast, “global” learners learn in large jumps absorbing material at random until they suddenly “get it” [12]. Table 1 displays these four-dimensions along with some key concepts pertaining to each index. This index of learning styles was used in developing active learning modules that effectively impact all learning styles.

Table 1. Learning styles categories [8].

Felder-Soloman	
ACTIVE	**REFLECTIVE**
Doing something active with it. Discussing, applying, or explaining it to others.	Thinking about it quietly first.
SENSING	**INTUITIVE**
Learning facts.	Discovering possibilities and relationships.
VISUAL	**VERBAL**
See-- pictures, diagrams, flow charts, time lines, films, and demonstrations.	Words-- written and spoken explanations.
SEQUENTIAL	**GLOBAL**
Gain understanding in linear steps.	Learn in large jumps, suddenly "getting it."

2.1.3 MYERS BRIGGS TYPE INDICATOR (MBTI) PERSONALITY TYPE

Along with the Felder-Soloman Index of Learning Styles, we used the Myers Briggs Type Indicator to guide our learning module development. In contrast to being learning style specific, the MBTI assessment is used to identify personality types. Originally developed from Carl Jung's theory of "Physcological Types", Myers and Briggs believed that each of us has a set of gifts or "mental tools" that we reach for in our everyday living and become comfortable using. Although within our psychological toolboxes we all have access to the same set of basic tools, each of us prefers a particular tool (or set of tools). It is from this unique set of preferences that our personalities arise [13].

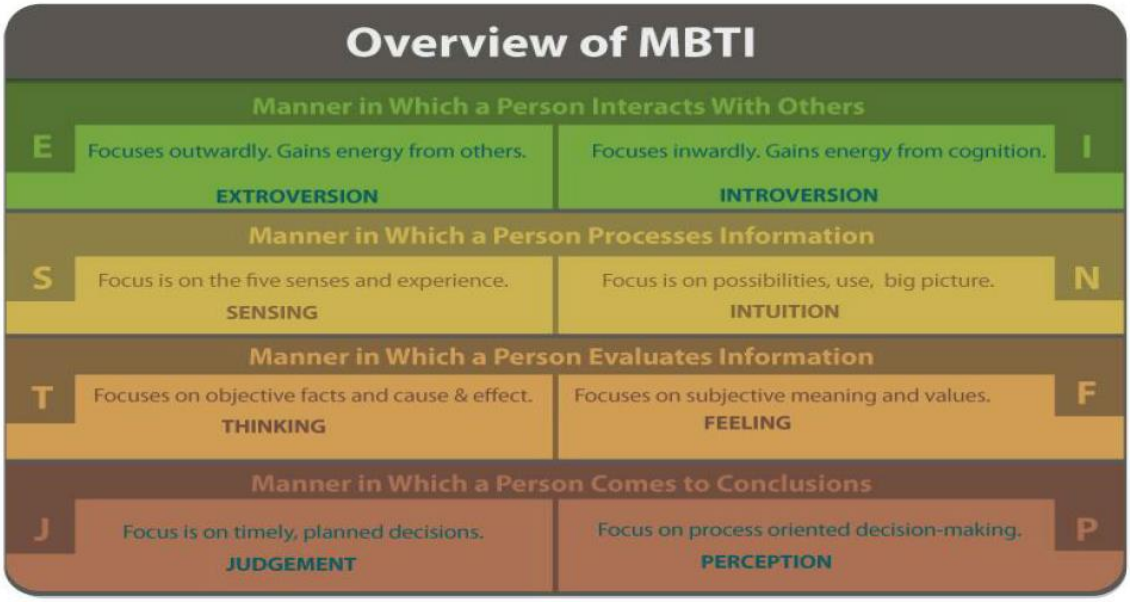
Based upon Jung's work, Myers and Briggs described the metaphorical tool box in terms of four dichotomies or pairs of preferences. As seen in Table 2, this first preference pair describes how individuals interact with the world around them. Extraverts (E) gain energy from action. They prefer to act, then reflect upon the action, and then act further. In contrast, Introverts (I) gain energy through reflection. They prefer to reflect, then act, and then reflect again [14]. Neither of these preferences (along with all other preference pairs) indicate aptitude, traits, or character, but rather they provide insights as to how individuals perceive the world and make decisions. No one preference is better than the other [13].

The second dichotomous pair indicates how people process/perceive information. Those who are more Sensing (S) prefer to look at the present tangible data, or in other words, the information that can be understood by the five senses. On the other hand, those who are more iNtiutors (N) prefer to dig into the data that is more abstract and theoretical. They are interested in the future possibilities and are more prone to go on "hunches". Within engineering education this preference pair is an interesting area of study because traditionally professors are generally iNtuitors and most engineering students are Sensors [12].

Thinking (T) versus Feeling (F) is the third MBTI pair and are functions of decision making, or how a person evaluates information. Those that are Thinkers, tend to detach themselves and measure the decision based upon what seems reasonable, logical and consistent with the cause – effect outcome they desire. Conversely Feelers tend to empathize with the situation and make the decision that provides the best balance and fit for the needs of those people involved.

Lastly, the fourth MBTI pair analyzes the manner in which a person comes to a conclusion. The Judging (J) types tend to be organized and prompt. They like having schedules and deadlines because it promotes order. For the Judgers the outcome is more important and rewarding than the actual process. Those that prefer Perception (P) tend to favor flexibility and spontaneity. Rather than planning for changes or new situations, they rather adapt when it comes. For Perceivers the process is more rewarding than the final outcome [14].

Table 2. Myers Briggs Indicator (MBTI) personality type [8].



Overview of MBTI			
Manner in Which a Person Interacts With Others			
E	Focuses outwardly. Gains energy from others. EXTROVERSION	Focuses inwardly. Gains energy from cognition. INTROVERSION	I
Manner in Which a Person Processes Information			
S	Focus is on the five senses and experience. SENSING	Focus is on possibilities, use, big picture. INTUITION	N
Manner in Which a Person Evaluates Information			
T	Focuses on objective facts and cause & effect. THINKING	Focuses on subjective meaning and values. FEELING	F
Manner in Which a Person Comes to Conclusions			
J	Focus is on timely, planned decisions. JUDGEMENT	Focus on process oriented decision-making. PERCEPTION	P

2.1.4 Development of the FE Learning Modules

The pedagogical foundation of the learning modules is based upon Kolb's learning cycle. The idea is to craft each learning module to facilitate students' learning of the material through active experimentation, concrete experiences, and reflective observations. In conjunction with this active learning process each learning module is tuned to appeal to all of the Felder-Soloman learning styles and MBTI personality types. By covering each of the modules' learning objectives with these aspects in mind, each student gains a more in-depth understanding of difficult engineering and FE concepts.

The FEA learning modules are designed for students who have little to no experience with FEA. The engineering problems are intended to be simple enough to solve but not obvious in their solutions; therefore, in order for the student to complete the assignment, he/she must use the FEA software. But due to the simple nature of the problem, the student can grasp the correlation between the computational model and the physical solution. Each module was first developed in PowerPoint and then made available to the students in PPT and PDF file formats. Each of the modules share a common format for development:

- References.
- Table of contents.
- Project educational objectives based upon ABET Criteria 3 for Engineering Programs.
- Problem description.
- Problem analysis objectives.
- General steps and specific step-by-step analysis.
- Viewing the results of the FEA.
- Comparison of FEA to another technique.
- Summary and discussion.
- Background information on finite element theory.

While using the provided template to develop the FE learning modules, professors are encouraged to design the module with the end learning objectives in mind:

1. Experiment with FEA theory.
2. Apply complex engineering concepts using computer models of engineering problems.
3. Examine typical steps in building a finite element model, such as selecting element type, loads, and boundary conditions.

4. Practice validating approximate finite element results with analytical solutions.

All of the FE learning modules use one of the following well known commercial FEA software packages:

- SolidWorks® Simulation (Dassault Systèmes SolidWorks Corp., Waltham, MA)
- SolidWorks® Flow Simulation
- MSC.Nastran (MSC Software Corporation, Newport Beach, CA)
- COMSOL Multiphysics® (COMSOL, Inc., Burlington, MA)
- ANSYS® ANSOFT (ANSYS, Inc., Canonsburg, PA)
- AdvantEdge™ (Third Wave Systems, Minneapolis, MN)

Once the learning module is designed by the professor it is uploaded to our research team's ALM Google site where it is peer reviewed by other ALM professors. Following the peer review and revisions the FEA learning module is ready to be implemented in the class room.

2.1.5 Example FE Learning Module

The structure and contents of the ALMs are illustrated in this section by describing an example module, the Rotating Shaft Fatigue Analysis module. This module uses SolidWorks® Simulation to perform FEA. After the table of contents, the educational objectives for the module are presented. As stated previously, the objectives refer to ABET criterion 3 [7, Criterion 3 (k)]. The objectives specific to this module are:

1. Understand the fundamental basis of FE Theory.
2. Understand the fundamental basis of engineering topics through the use of finite element computer models.

3. Construct a correct computer model using commercial FE software.

4. Interpret and evaluate the quality and accuracy of the finite element solution.

The analysis objective for this module is estimation of the fatigue life of a rotating shaft under a steady load using SolidWorks® Simulation software. The student is expected to learn to define a fatigue study, define an S-N curve for the material, define constant-amplitude fatigue loads, and interpret the fatigue results. The description of the problem that provides focus for this module is shown in Figure 2.

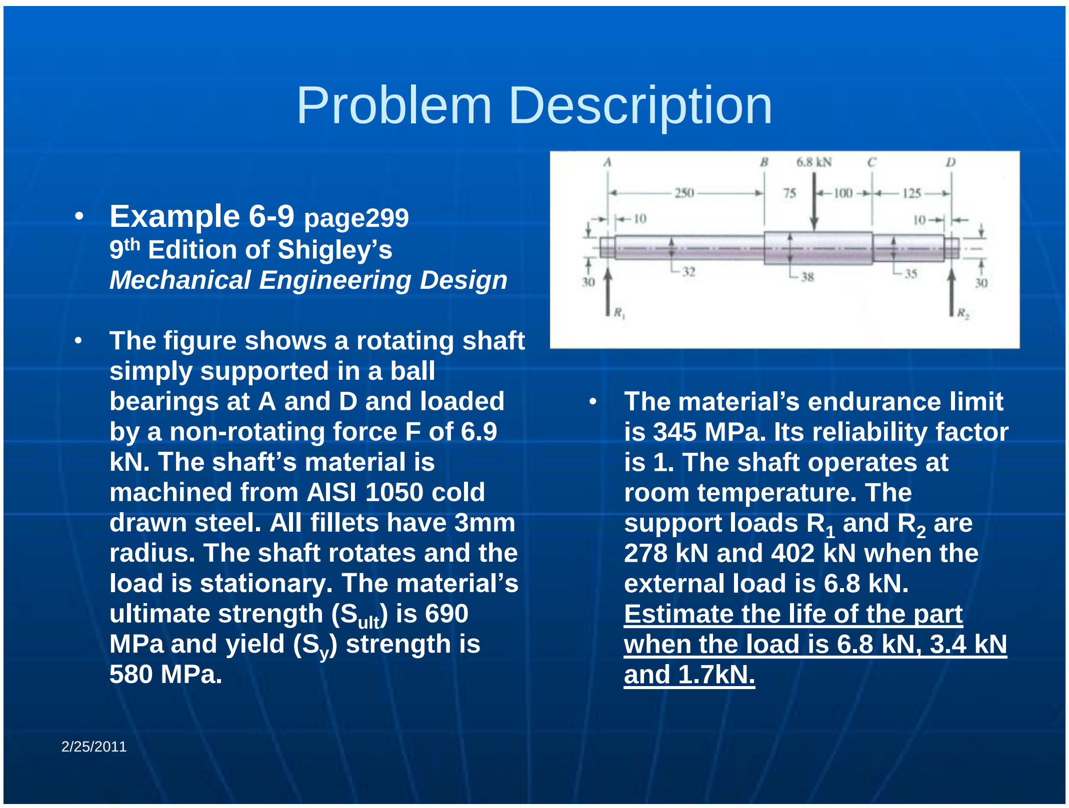


Figure 2. Problem description for fatigue analysis.

Much of the remainder of the module provides specific, detailed instructions on creating the FE model, performing the analysis, and displaying and interpreting the results. This part of the module begins with an overview of the tutorial, shown in Figure 3.

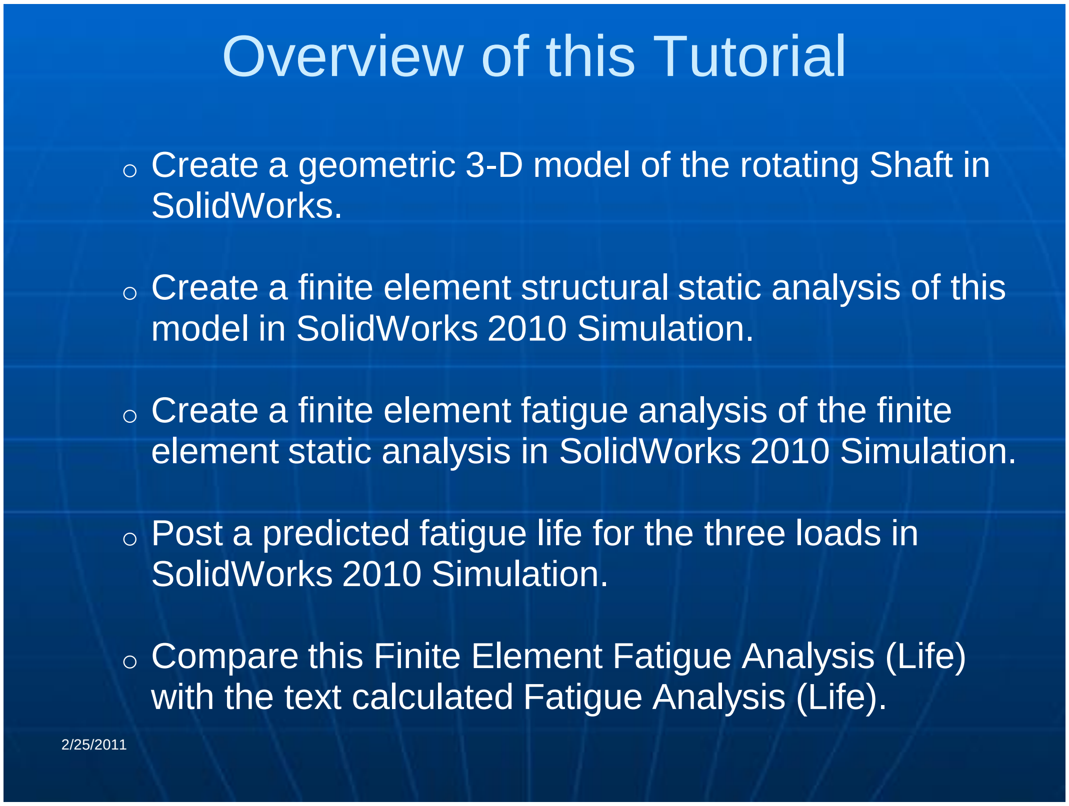


Figure 3. Overview of rotating shaft analysis tutorial.

The tutorial provides step-by-step instructions on modeling the geometry of the shaft in SolidWorks®. This part of the module begins with a brief orientation of the interface to the program, showing the locations of necessary command icons. The steps to set dimensions and create the shaft geometry are then presented. The final shaft geometry is shown in Figure 4 .

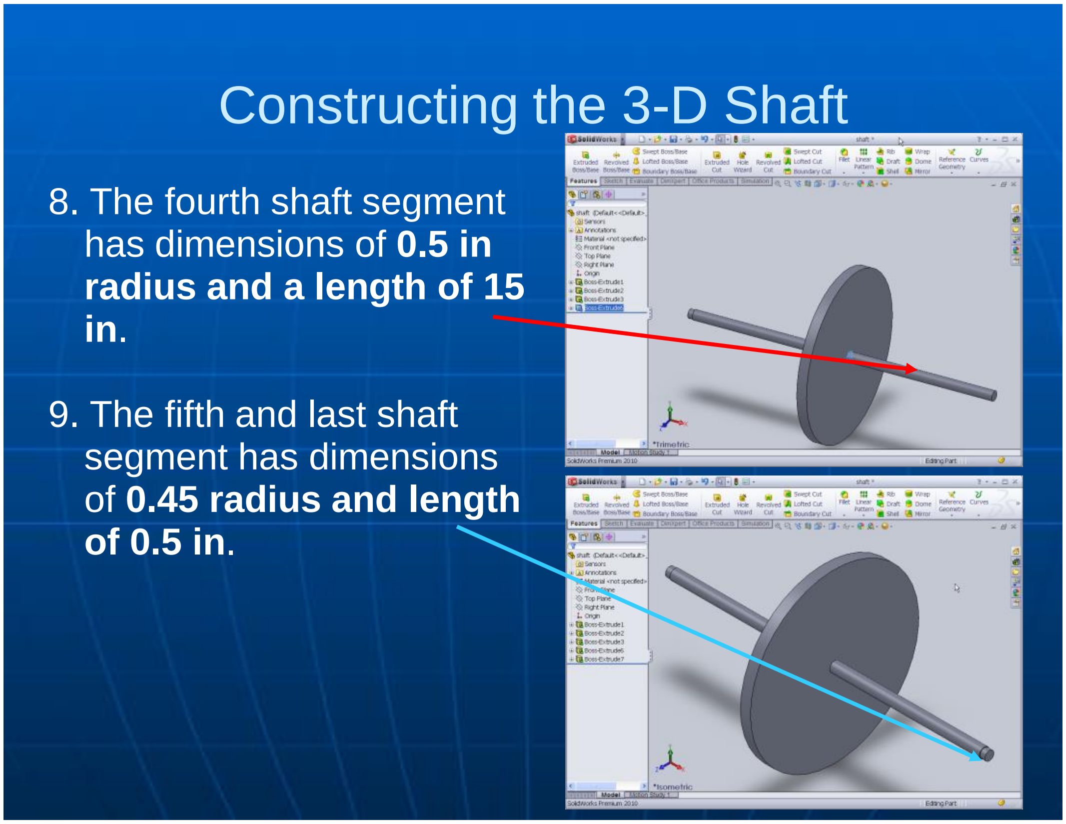


Figure 4. Rotating shaft geometry.

After the geometry is defined, the tutorial proceeds through application of loads and boundary conditions. Then the steps for meshing the geometry and running the static structural analysis are presented. The student is then led through the steps to create a fatigue study from the results of the static analysis. The results of this study are displayed for the student to interpret. An example of the results of the fatigue study is shown in Figure 5.

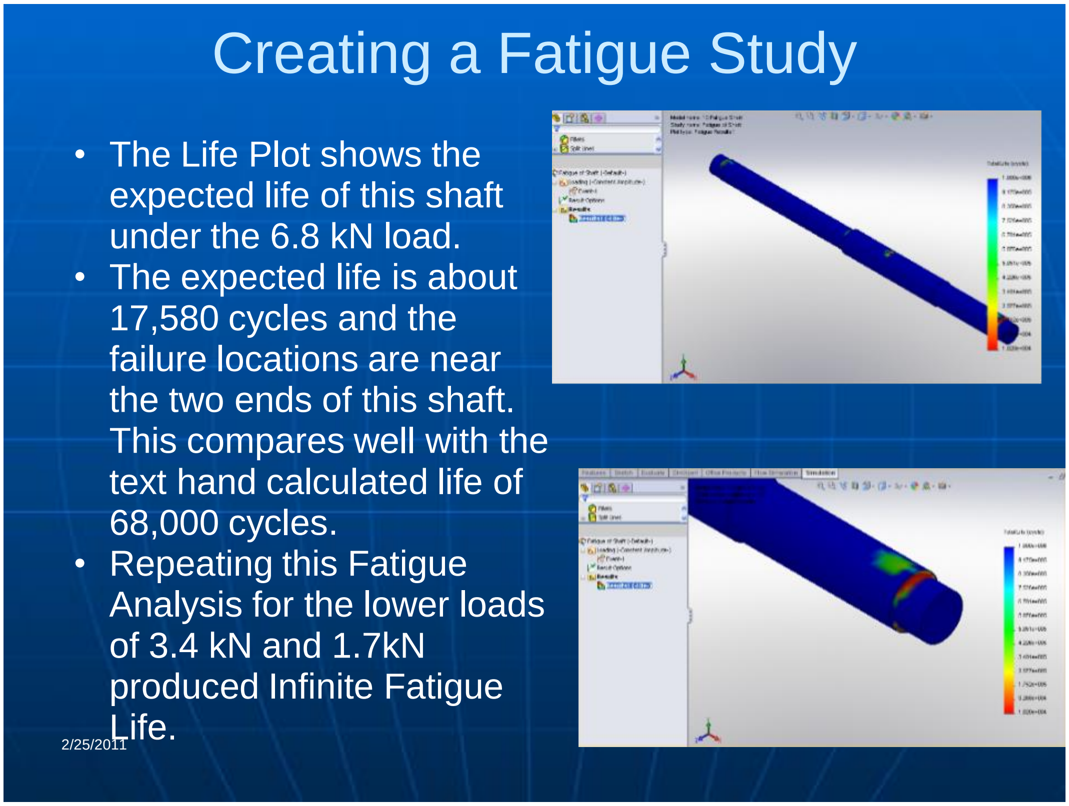


Figure 5. Results of fatigue analysis of rotating shaft.

Finally, the tutorial leads the student through a comparison of the solution in the reference text with the solution obtained from the FEA. The module also contains a summary of FE theory as an appendix. Details of this module and the others created for this project are available at https://sites.google.com/site/finiteelementlearning/home.

2.2. Assessment Methodology Overview

The developed FE learning modules were evaluated by statistically analyzing the students' improved understanding of the concepts taught across all learning styles and personality types. Ultimately we want to accurately and thoroughly assess the learning modules to ensure they are effectively meeting the needs of all students. To achieve these assessment goals we have developed a fourfold project assessment:

1. Assessment Methodology – Develop and implement an iterative assessment system.
2. Statistical Measures – Determine improvement in student learning across distributions.
3. Equitability Study – Gain insight into the effectiveness of the FE learning modules across various personality types and learning styles.
4. Feedback and Improvement – If the learning module is not effective for a particular demographic, personality type or learning style, improve the module to address their needs. Students also evaluate and provide feedback for the ALM.

2.2.1 Assessment Methodology

There are two major parts to assessing the effectiveness of the active learning modules. The first is to establish a baseline understanding of the student's background, demographic, and learning style. The second is to create an assessment instrument to evaluate the student's understanding of the FE concepts.

We gather information from the students through the use of surveys. Due to confidentiality and sensitivity of the information we gather, at no point is the information correlated with the student's actual identity. In order to disassociate the students from their personal data, each student is assigned an animal name (student id) to use for all of the surveys. This way, we as researchers, do not know who is doing the learning module but can keep each student's data together. The background/demographic survey gathers information about the student's:

A. Demographics – academic major, educational level, grade point average, expected grade earned in current course, reason for taking course, plans after graduation, age, ethnicity, and gender

B. Felder-Soloman learning styles and MBTI personality type

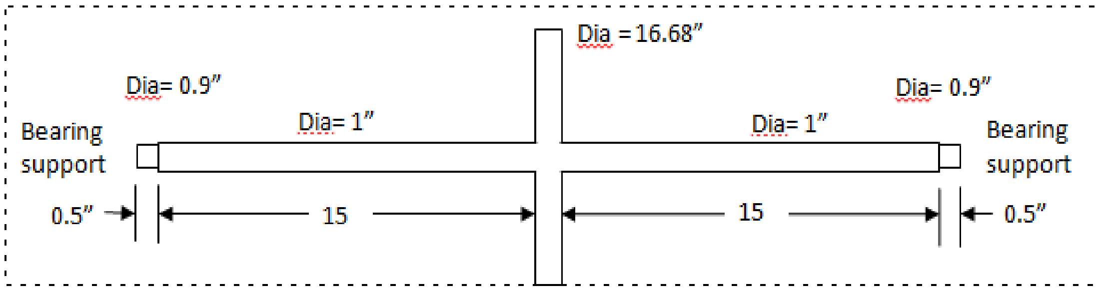
C. Animal name (student id) – used to link individual student's data with future evaluations and survey responses.

The background/demographic data is generally used to evaluate the effectiveness of the learning modules across all the varying types and groups of students. A sample of the demographic survey can be found in Appendix A.

The actual assessment of the learning module itself comes from measuring the difference of the students' understanding of the concepts before and after completion of the ALM. This is done by administering a multiple choice quiz. The content specific quiz is first issued to the students after the FE material is presented in class, but prior to the students being exposed to the learning module. This first quiz serves as a baseline and shows the level of understanding if the students were only given a traditional lecture. This ideally isolates the effects the FE learning module had in teaching the students.

The learning module is then given to the students to work through. Following the completion of the learning module, the same quiz is administered to the students. The pre- and post-quizzes are correlated together by the student's id (animal name) and linked to their demographic data. Below, in Figure 6, are some example questions for the fatigue analysis module that was described previously.

A steel shaft shown with a 31-in span between two bearings, carrying a drum in the middle



Circle the best answer

1. When the shaft has larger modulus, the natural frequencies
   a) become larger
   b) become smaller
   c) do not change
   d) sometimes become larger, sometimes become smaller
   e) none of the above

2. In a rotating shaft system, what type of vibration exists?
   a) lateral vibration
   b) shaft swirl
   c) torsional vibration
   d) all of the above
   e) only lateral vibration and shaft whirl

3. When the rotating speed of the shaft increases, the natural frequencies
   a) become larger
   b) become smaller
   c) do not change
   d) sometimes become larger, sometimes become smaller
   e) none of the above

4. When the drum position along the shaft changes, the natural frequencies
   a) become larger
   b) become smaller
   c) do not change
   d) sometimes become larger, sometimes become smaller
   e) none of the above

Figure 6. Example Pre/Post Quiz Questions

2.2.2 Statistical Measures

The data were collected and compiled into a format readable by SPSS (Statistical Package for the Social Sciences, IBM, Armonk, NY) software. A detailed administrative protocol for preparing the files for SPSS can be found in Appendix B. SPSS is a widely used and very powerful statistical analysis tool. Once the data are compiled into the correct SPSS format a wide array of automated statistical analyses can be performed. The following statistical measures were performed [2]:

1. Dependent samples t-tests were conducted in order to analyze whether or not exposure to the module significantly improved student performance on the pre-post measure, given before and after module implementation.
2. Independent samples t-tests were conducted to compare improvement on the pre-post measure for each personality type, learning style, ethnicity, and gender subgroup. The purpose was to examine whether or not any subgroup might have benefitted more (i.e., improved more from pre-test to post-test) from exposure to a module than another.
3. Beginning in the third year of implementation, Mann-Whitney analyses were conducted in addition to the independent samples t-tests. These analyses are generally more stringent than t-tests and do not assume that the scores in the population are normally distributed. The assumption of normal distribution is generally made when samples sizes are larger (i.e., justified by the Central Limit Theorem). The Mann-Whitney analyses were appropriate to utilize for the current study because the sample sizes being analyzed tended to be small.

Until recently, our team has evaluated the pre-post measure of the quiz scores according to:

$$Percent\ (\%)\ Improvement\ =\ [\frac{post\ quiz\ score-pre\ quiz\ score}{prequiz\ score}] * 100 \qquad \text{EQ. (1)}$$

The equation above is a generic percent improvement assessment that is widely used, but we noticed that the equation is not normalized across the whole range of improvement. For example, let's say the students for module A improved their scores from 40 to 50 (out of 100) and students for module B improved their scores from 80 to 90 (out of 100). We can see that both sets of students improved their scores by 10 points, but according to EQ. 1, module A has a percent improvement of 25% while module B has a percent improvement of 12.5%.

Through a literary search we found a large number of researchers who follow a method of performance evaluation proposed by Hake [15]. His research involved using pre/post test data to evaluate the effectiveness of physics courses. The equation below is his measure of improvement, or what he calls "the average normalized gain <g>", where the angle brackets indicate class averages:

$$< g > =\ [\frac{<post\ quiz\ score> - <pre\ quiz\ score>}{100- <prequiz\ score>}] \qquad \text{EQ. (2)}$$

This equation gives the ratio of actual score improvement over the total possible improvement. According to Hake this equation was established long before him:

> This half-century-old gain parameter was independently employed by Hovland et al. (1949), who called g the "effectiveness index"; Gery (1972), who called g the "gap-closing parameter"; Hake (1998a,b), who called g the "normalized gain";

> and Cohen et al. (1999), who had the good sense to call g what it is, namely "POMP" (Percentage Of Maximum Possible). [16]

When we employ this method for the example given above of module A and B, module A would have 16% total improvement and module B would have a 50% total improvement.

This evaluation tells the clearer story of how much students improved relative to the potential they could improve. The previous version gave a false view that low performing module scores had a greater percent improvement based upon their initial low baseline score.

2.2.3 Equitability Study

Through the use of the pre/post quizzes we can determine if the class as a whole is improving. Although an overall improvement is a desired outcome, it does not indicate if all students are being best served by the active learning modules. There could be subsets within the class whose needs are not being met. To evaluate the effectiveness of the ALM for all students we use the learning style data collected in the demographic survey and cross-analyze it with the pre/post-quiz results.

Following our scrupulous data analysis, the administering ALM professors are provided with a summary of how their students improved. In the event that a demographic or learning style sub-group performs statistically lower ($P \leq 0.05$) than the class as a whole, the professors are provided general feedback on how to adjust their ALM to meet their needs.

2.2.4 Feedback and Improvement

The process of continual improvement is critical to the success of this research because our goal is to be effective educators who can adapt according to the needs of our students. To ensure the quality of our ALMs we have a two-fold refinement process.

The first, as mentioned in the previous section, is providing feedback to ALM developers on how to adjust their learning modules to meet the needs of under-performing demographics, personality types or learning styles. For example, if our analysis shows that introverts are statistically ($P \leq 0.05$) benefiting less than extroverts, we suggest changes to the ALM that are tailored to introverts. Some of these changes could comprise: include or change a couple activities to be completed alone, insert periodic questions that cause reflection and develop ideas internally, add more word descriptions, or include an individual problem solving process. The idea here is to make a few minor adjustments to help a small sub-group without taking away from those that are already performing well. It is critical to maintain balance between all the different learning styles and personality types.

The second aspect of ALM refinement is gathering feedback from the students. As learners of the content, the students provide great insights on formatting, content structure, difficulty of the concepts, time to complete, usefulness of the module and open-ended feedback for the professors. We have created a general student follow up survey that can be used for all of the ALMs (see Appendix C) but have also given professors the option of customizing the student survey for the specific ALM. These surveys are coded up, similar to the demographic survey, in Qualtrics online survey software (Qualtrics, Provo, UT). The URLs are then issued to the students for easy access.

2.3. Results

We are currently in our eighth year of this research. To date we have 29 active learning modules and have administered to 833 students from 7 universities. Participating universities include: University of Pacific, California State Polytechnic University – Pomona, Gonzaga University, Washington State University, Tuskegee University,

University of New Haven, and the United States Air Force Academy. Other supporting universities include The University of Texas at Austin and The University of Arkansas.

2.3.1 STUDENT IMPROVEMENT

We amalgamated the data from all implementation years. The complete data set can be found in Appendix D. Table 3 below contains a summary of our analysis.

Table 3. Combined ALM Results

Number of Modules Implemented	Total Number of Students	Average Pre-Quiz	Average Post-Quiz	Delta (Post-Pre)	Average % Improvement (EQ 1)	Average Normalized Gain (EQ 2)	Normalized Gain T-Test
55	833	54.4%	71.5%	17.1%	31.3%	37.4%	$P < 0.001$

We found the average student improvement across all years of implementation to be 37.4%. This was calculated using EQ. (2) for average normalized gain. As mentioned earlier, we previously calculated student improvement using an average % improvement as noted in EQ. (1). The values of these two equations are compared in the Table 3. Although there is only a difference of 6.1% ($P = .427$) between these assessment values for the complete data set we believe the average normalized gain (EQ 2) tells a more complete story. Across all 55 ALM implementations students improved by 37.4% ($P < 0.001$) of the total possible improvement.

For the aforementioned improvement, we have found that 87.5% of the modules demonstrated a statistically significant ($P \leq 0.05$) student improvement. Meaning that for 87.5% of the modules implemented, we are 95% confident the ALMs increased student performance. When including data sets that showed moderate statistical significance ($P \leq 0.10$) we found that 93.8% of the modules at least moderately increased student performance.

2.3.2 ILS AND MBTI SUBGROUP DIFFERENCES

Significant differences in improvement between ILS and MBTI subgroups were NOT identified in two-thirds of the modules implemented (67%). This suggests that these modules did not benefit one personality type or learning style over another. For the 33% of the modules that did favor one subgroup over another, we provided feedback to the professors on how to refine their learning modules to mitigate these differences.

2.3.3 GENDER AND ETHNICITY DIFFERENCES

Due to small sample sizes it is difficult to analyze ALM effectiveness across gender and ethnicity differences within every module implemented. For the classes in which our ALMs are implemented the students are predominantly male. During Phase II Year 3 we had one class that appeared to have a large enough sample to analyze gender differences. As seen in Table 4, despite the 10 point difference in deltas the sample size was too small to show statistical significance.

Table 4. Gender Differences in Delta for Phase II Year 3 Learning Modules

Module	Semester	Institution	Gender	Students (n)	Mean Delta	Significant Difference
Sheet metal forming using FE Analysis: Shallow Drawing of a Circular Sheet	Spring 2012	Tuskegee	Male	7	2.9	No (p=.218)
			Female	7	12.9	

Delta = post-quiz score minus pre-quiz score

In addition to gender differences, our sample sizes of different ethnic groups are low. Table 5 shows a few modules that were analyzed across ethnic differences. Only the Asian/Pacific Islander and White/Caucasian students were compared due to their similar sample sizes.

Table 5. Ethnicity Differences in Delta for Phase II Year 3 Learning Modules

Module	Semester	Institution	Ethnicity	Students (n)	Mean Delta	Significant Difference
Computational Fluid Drag of Bobsled Model	Fall 2012	UoP	Asian/Pacific Islander	4	27.5	No (p=.588)
			White/Caucasian	2	20.0	
Machining Analysis during Chip Formation	Spring 2013	UoP	Asian/Pacific Islander	7	16.9	No (p=1.000)
			White/Caucasian	7	16.9	
Curved Beam Stress	Fall 2012	UoP	Asian/Pacific Islander	12	16.7	No (p=.397)
			White/Caucasian	16	19.8	
Critical Speed of Rotating Shaft	Fall 2012	UoP	Asian/Pacific Islander	10	7.0	No (p=.924)
			White/Caucasian	15	6.7	
Thermal FEA: Semi-Infinite Medium & Steady State Heat Conduction	Spring 2013	UoP	Asian/Pacific Islander	10	3.3	No (p=.192)
			White/Caucasian	13	12.2	
Power Analysis of Rotating Transmission (Shaft Stress)	Spring 2013	UoP	Asian/Pacific Islander	10	2.4	No (p=.224)
			White/Caucasian	15	1.3	

Delta = post-quiz score minus pre-quiz score

In the analysis presented above it appears that the change delta was not different between the represented ethnic groups. But once again these small sample sizes lack the statistical power to detect or rule out subgroup differences. However, these preliminary results suggest that these modules do not favor one gender or ethnicity over another.

2.3.4 Student Feedback Survey

Following the completion of the ALMs, students are issued a general feedback survey. The survey asks students the level for which they agree or disagree with a statement about the learning module. The students are also asked open-ended questions regarding their experience while working through the module. Appendix C contains a sample general survey. We analyze the collected data and present it to the professors in table format. Table 6 shows an example of a few lines from an analyzed student survey. Item by item the professors can see how well their ALM specifically addresses the desired learning outcomes.

Table 6. Example Student Survey Results

	Number of Student Respondents (n)					*Percentage of Valid Responses (%)*						
Survey Item	Disagree	Generally Disagree	Neutral	Generally Agree	Agree	Disagree	Generally Disagree	Neutral	Generally Agree	Agree	***M***	***SD***
1. These activities helped me understand thermal analysis in a conceptual manner.	0	0	3	18	8	*0*	*0*	*10.3*	*62.1*	*27.6*	4.17*	.602
2. These activities showed me that the finite element method determines an approximate solution for thermal analysis problems.	0	0	2	10	17	*0*	*0*	*6.9*	*34.5*	*58.6*	4.52*	.634
3. Activities like these, and similar ones done by												

We started issuing these surveys starting in 2011 and have collected feedback for 18 ALMs. From the data collected we found that 87.3% of the ALMs had overall favorable reactions from the students. When asked how the learning module might be improved some student answers included:

- Correct typos, explain procedure before handing students the project.
- More detailed instructions. Don't make the surveys too long.
- More detailed instructions for the plotting.
- Could be more interactive, demonstrating more potential errors.
- A PowerPoint is useful, but creating a video that walks students through the work could be helpful. I think that the theoretical background would better be presented in a lecture.
- Some slides are too wordy, with a little too much unnecessary details in them.
- More detailed instructions and explanations for what and why I do each step.
- Provide slides with summary of the past few slides.
- The use of more powerful computers so the simulation doesn't take a half hour to run.
- The module is already very well laid out, just maybe update the commands to better fit the 2013 SolidWorks® update.
- Overall very thorough.

The student surveys are possibly the most valuable feedback the professors receive. As the modules continue to be implemented in the future they will be further refined based on these student suggestions.

2.4. Conclusions and Future Work

This thesis has summarized the work of eight years of active learning module development. Overall our ALMs have shown to improve student performance by a normalized gain of 37.4% ($P < 0.001$). We also found that 87.5% ($P \leq 0.05$) of the implemented ALMs increased student performance. Considering that these ALMs are designed to supplement traditional lectures of engineering concepts that are typically difficult for students to understand, we find these student performance improvements to be significant.

In the coming years we plan to continue our iterative improvement of the 29 ALMs for all learning styles and MBTI categories. We also seek to recruit more schools to participate in our research in order to increase our sample size. As more professors join in the research we will expand the types of modules we offer. With an increased sample size we will be better suited to analyze demographic and learning style subgroup differences.

2.5. ALM Research Acknowledgements

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CHAPTER 3: PROTOTYPE STRATEGY DEVELOPMENT

Prototyping is one of the most critical phases in product development and yet many companies do not have a systematic approach for repeatable results. In fact prototyping is often guided ad hoc by experience. To provide a more pragmatic approach, this research seeks to introduce and evaluate effects of a novel method for designing prototyping strategies.

Two years in the making, we have created a tool to guide product development teams in their prototyping efforts. This tool has evolved through a series of iterations and tests. This evolution process is in this thesis, but the main focus remained the same throughout its development, which is, to provide a systematic translation between design context variables and practical planning for a prototyping effort.

In particular our tool guides designers through six critical prototype strategy choices: (1) How many concepts should be prototyped? (2) How many iterations of a 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?

We assessed the planning tool in two environments: (1) a controlled experiment in which volunteers completed a prototyping design challenge, and (2) a capstone design class with a diverse range of open-ended sponsored design projects. In both cases, students received training for the method and then employed it in their own efforts.

In our study the new tool caused student teams to employ significantly more efficient and effective prototyping strategies, such as prototyping early and often. The results indicate a higher functional performance of prototypes from groups using the new planning tool compared to control groups. This thesis describes the evolved prototyping strategy planning tool, details the multiple sets of experiments, and discusses results. Much of this work is a combined effort of several researchers and has been published previously. References to those publications will be made throughout to ensure credit is given for this collaborative effort.

3.1. Background and Motivation

Prototyping is a promising frontier for design methodology research advances. Research shows that prototyping decisions are often based on practical knowledge and management approaches rather than experimentally tested methods [17,18,19,20,21,22,23,24]. Simultaneously it has been shown that perhaps the greatest portion of sunken costs in new product development occurs during the prototyping process [25]. Therefore, a methodical tool to help teams direct their prototyping efforts could be a great asset to mitigating improper use of time, money, and other resources.

A number of projects have explored heuristic observations of better practices in prototyping. Viswanathan, *et al*. conducted an in-depth tracking study of graduate design students to determine beneficial practices of prototyping [26]. Their experiment involved data collection over three semesters of a graduate design course. These results include foundational open-ended heuristics such as “use standardized parts” and “support building with analytical calculations.” An in-depth DoD study makes the following observations on best practices over forty years of prototyping: [27]: 1. Make sure the (final) prototype meets the minimum design requirements; 2. The goal of a prototype is to prove that the final product is viable in the real world; 3. Prototypes are intended to be focused on determining unknown quantities; therefore, avoid adding non-critical features; 4. During prototyping there should be no commitment to production; 5. Once the design process is underway, do not add design requirements or performance expectations.

Another set of research efforts explored modeling techniques to hypothesize the number of prototypes to increase profit and decrease risk. Dahan and Mendelson find that sequential designs succeed in cost-constrained environments while parallel designs succeed in time-constrained environments [28]. Thomke [29] and Thomke and Bell [30] add that significant savings can be achieved through multiple low fidelity prototypes. Dahan's [28] equations leverage basic assumptions for the uncertainty of success of a prototyping effort and the marginal increase in profit that results from that effort.

An additional set of empirical studies evaluates the effects of controlling these strategy variables one at a time and measuring design outcomes. Haggman, *et al*. [31] tracked the activities of mid-career professional graduate students during the preliminary design phase, examining various correlations between 'throwaway' rapid prototyping and performance metrics. They found that building prototypes early in the design process correlated positively with success, while the total amount of time spent did not. Similarly, the lower performing teams prototyped later in the process. Kershaw, *et al*. [32] found that teams which developed prototypes earlier identified and positively reacted to flaws in their designs, and developed countermeasures or improvements compared to teams that prototyped later in the process or did not develop multiple prototypes. Yang [33] furthermore, shows that time spent testing is positively correlated with outcome and conversely, time spent fabricating is negatively correlated with outcome. Jang confirms in another, independent empirical study that more successful teams prototype earlier and more often throughout the entire process [34]. Dow [35] conducted a controlled study requiring half the participants to iterate and requiring the other half to focus all available time on one prototype without iteration. This study empirically confirms that, in the circumstances tested, pursuing at least three additional iterations beyond development of a single prototype significantly improved final design performance.

Most of the studies reviewed above are of one of two types, either observation of designers' practice without external control or evaluation of strictly enforced single strategy variable studies. This first type is critical to identify best practices. The second type is critical to determine if the practices and their results are repeatable. We developed an experimental approach to explore (1) if designers will actually apply these heuristics in their own practice when provided with a method at the outset of prototyping; and (2) if these teams will in fact outperform control groups that do not employ the method.

3.2. Quantitative Prototyping Strategy Method

Our goal in this research is to give design teams a systematic approach to developing a planned prototyping strategy. A prototyping strategy is defined here as *the set of decisions that dictate the actions to be taken to accomplish the fabrication and testing of the prototype(s)* [36]. To meet this goal, we devised a method to translate design context variables (independent variables) into prototyping decisions (dependent variables). In the extensive literature given previously we identified the best prototyping practices. Our first edition of the prototyping strategy methodology attempts to incorporate these best practices into a set of guiding questions with corresponding flowcharts and foundational equations. These method elements assist the designer to make choices for approaching the prototyping process in an efficient and effective manner.

3.2.1 Synthesized Prototyping Design Context Variable

The heuristics explored by Moe [36], Christie [37], and Viswanathan [26] provide a foundation from which we have synthesized a list of variables for a prototyping strategy. In other words, this list represents several relevant choices a design team will likely face during prototype development (Table 7, [38]). This list was formed by translating the prototyping heuristics into the implicit decisions that must be made. For example a heuristic “build a scaled prototype” translates into the decision “build a scaled prototype or build an exact prototype”. We have generalized these decisions to be applicable to a wider range prototyping circumstances. For instance we changed specific concepts such as “avoid complicated machining” to the more generalized decision form “ad hoc or precise embodiment”. The generalized form is now applicable to those who are not necessarily machining, and acknowledges that all physical prototypes must be embodied in one way or another.

Table 7. Hierarchical List of all Decisions for a Broad Prototyping Strategy.

Scale	Scaled or actual boundary conditions/parameters	
	Scaled or actual function	
	Scaled or actual geometry (dimensions, shape, tolerances)	
Integration	Physical integration or segmentation/subsystem isolation	
	Functional integration or segmentation	
Logistics	**Allocations**	Rigid or flexible scheduling
		Rigid or flexible budgeting
	Make	Number of design concepts (in parallel)
		Number of iterations of each concept
Embodiment	COTS (Commercial Off-the-Shelf) or custom parts	
	Material	Actual or easy to manufacture
	Method	*Ad hoc* or precise (formal or systematic)
	Virtual or physical	
	Outsourced or in-house	
Evaluation	Relaxed or stringent parametric design requirements	
	Exploration or verification	
	Testing	Dynamic or static
		Run conditions or failure conditions
		Multiple test conditions or single condition
		Continuous or discrete variation of parameters

To provide scope for the research, we have chosen to focus on five dependent prototyping strategy variables as an initial foundation for developing this prototyping strategy methodology:

1. Number of design concepts
2. Number of iterations of each concept
3. Scaling
4. Subsystem isolation or design of integrated system
5. Relaxation or rigid application of design requirements

We recognize that this is not a comprehensive list, but it is a good starting point. We believe these variables can be derived from six independent context variables:

1. Budget
2. Time
3. Difficulty of meeting the design requirements
4. Interactivity
5. Designer's experience
6. Rigidity of design requirements

The relationship and translation from independent to dependent prototyping variables are discussed hereafter.

3.2.2 Method Overview

The purpose of the prototyping strategy method is to provide a means for designers to systematically make prototyping decisions. Our method does this by taking independent context variables that are unique to each designer's product and translating them into actionable dependent prototyping decisions. Prior to delving into the correlation between the independent and dependent variables it is pertinent to recognize the assumptions we made in development of the method:

1. An effective and efficient initial prototyping strategy plans to exhaust resources, regardless of anticipated ease in meeting design requirements.

2. The effective and efficient prototyping strategy is one that maximizes profit or design performance [28].
3. The more iterations of a single concept, the more likely one of them will be successful at meeting the design requirements [36].
4. The more concepts that are developed in parallel, the greater likelihood of determining the best concept [36].
5. The more experience a designer has, the more likely they are to develop a prototype that meets the design requirements in the fewest prototype iterations.

These assumptions were derived from our review of the prototyping literature and generally accepted prototyping theory. As noted previously, this method does not address every possible prototyping strategy variable. The variables we have chosen to focus on have been identified as some of the most critical to success, especially at the onset or during early phase prototyping.

Number of Iterations

Determining the number of iterations is directly correlated to minimizing uncertainty. There is a fine balance between determining the number of iterations for a single concept and the number of concepts to prototype in parallel. When uncertainty is high it is likely that more iterations will be needed in order to meet all design requirements and maximize performance. As time and resources are allocated towards more iterations of a single concept the designer is less likely to be able to pursue multiple design concepts in parallel. On the other hand, when uncertainty is low the designer is freer to explore the design space.

To quantify uncertainty we have deduced the following equation [38]:

$$U = \frac{\left(\frac{Req+D}{2}\right)}{E_x}, \qquad \text{EQ (3)}$$

where E_x is the designer's experience, R_{eq} is the rigidity of the design requirements, and D is the anticipated difficulty in meeting the design requirements (with a particular design concept) [38]. The values of the variables are estimated by the designer on a Likert scale from 1-10.

Scaling, Subsystem Isolation and Relaxation of Requirements

To assist designers in determining whether or not they should scale, isolate subsystems, or relax the design requirements Camburn [38] created a series of flow charts to translate the independent design context variables to these design choices.

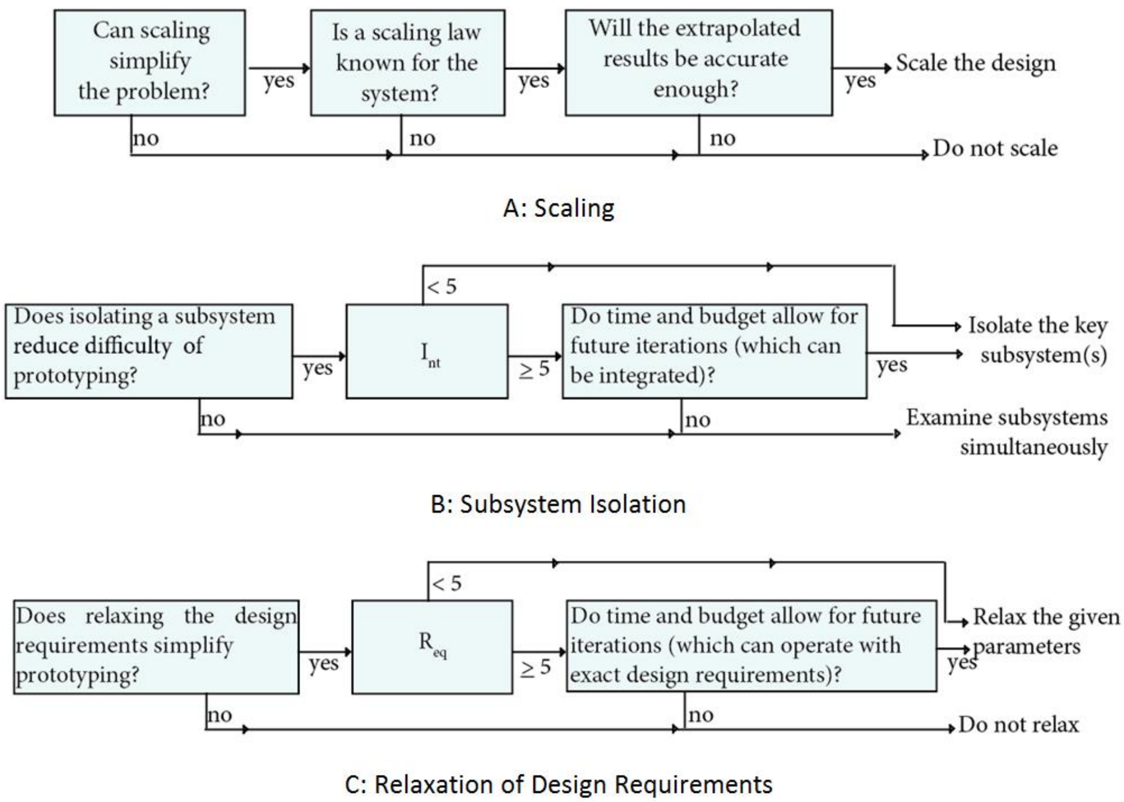


Figure 7. Preliminary Flowcharts for Determining Scaling (A), Isolation (B), and Relaxation (C)

As seen in Figure 7 these flow charts ask designers a series of questions to guide their decision making process. The flow charts are one of the novel contributions of our prototyping strategy method. They take into account the prototyping techniques outlined by Viswanathan et. al. [26], Christie et al. [37] and Moe et al. [36]. Each of the flow charts should be used for each iteration that will be built.

Table 88 defines the scaling, isolation and relaxation (SIR) variables and provides a brief example of their application [38].

Table 8. Definitions of SIR

S/I/R	Definition	Example
Scaling	Scaling proportionately changes the size of the prototype. It is useful when the actual device size is too difficult or costly to produce or test.	A navy ship is built at ~1/100 scale the first several iterations.
Subsystem Isolation	With subsystem isolation, one of the subsystems of the device can be prototyped or experimentally evaluated while other subsystems are prototyped independently or not at all.	Monitor design project- prototype the LCD array but ignore casing design.
Relaxation of Design Requirement	With functional requirement relaxation, the values or parameters of the design can be altered to simplify prototyping.	Prototype a new engine- spec it to run at ½ designated torque for the prototype.

The first flow chart depicted in Figure 7 helps designers decided whether they should scale their prototype. The flow chart encourages scaling only if it will simplify the problem, if a scaling law is known, and if the scaled model will yield results accurate enough to predict the design requirements. If any of these parameters does not hold true, the designer is prompted not to scale the prototype.

The second flow charts examines whether or not the designer should isolate and focus upon a subsystem as opposed to building and testing the system as a whole. Subsystem isolation is encouraged if it simplifies prototyping and if the subsystem is relatively un-integrated. The level of integration (or interactivity, I_{nt}) is determined by the designer when working through the method survey. Here, interactivity, I_{nt}, is defined as the *qualitatively assessed value of a design on a scale of one to ten that describes the level at which subsystems are dependent on each other for operation* [38]. For example a Swiss army knife has a low I_{nt} value because each of the tools can function relatively independently. In contrast, a heat exchanger in a cooling system has a very high I_{nt} value because the subsystem components (heat exchanger, hot fluid pump and cooling fluid pump) are highly dependent upon one another to function.

The third flow chart guides designers in determining if they should relax the design requirements and build their prototype to function at requirements less than originally specified. The purpose of design requirement relaxation is to simplify the prototyping process and allow designers to analyze functionality and features quickly without the rigidity of meeting final design requirements. Design requirement rigidity, R_{eq} , is a qualitative value determined by the designer in the method survey. The value represents *how inflexible the parametric values of the design requirements are on a one to ten scale* [38]. For example R_{eq} would be low for a proof-of-concept prototype and high for an Alpha prototype. When determining if the design requirements should be relaxed for the prototype it is also pertinent to evaluate whether or not there is enough time and budget for future iterations which will meet the exact design requirements.

Concepts in Parallel

As designers work through the method, once they have determined the number of iterations for each concept and their SIR. choices for each iteration, they will then need to estimate the cost of each iteration. Here we define cost in terms of both dollars and person hours. The total cost of a concept is the sum of the cost of all iterations necessary to meet the target functionality. To determine if a concept should be built, designers are prompted to evaluate the cost of their most promising concept first. If there is time and money remaining they are then prompted to estimate the cost of their next best concept. Equations 2 and 3 below show how the method calculates remaining budget.

Remaining budget after concept A:

$$B_t - \sum_{i=1}^{I_{t-A}} C_t(ith\ iteration\ of\ A) \qquad \text{EQ (4)}$$

Remaining budget after concept A and B:

$$B_t - \sum_{i=1}^{I_{t-A}} C_t(ith\ iteration\ of\ A) - \sum_{i=1}^{I_{t-B}} C_t(ith\ iteration\ of\ B) \qquad \text{EQ (5)}$$

Here, B_t is the total available time (person hours) for the entire prototyping effort, C_t is the cost of the iteration in person hours, I_{t-A} is the number of iterations for concept A. These equations are used both in terms of dollars and person hours. The limiting resource (money or time) determines if the concept should be pursued. For example, with a given budget of $200 and 30 person hours, the design team estimates Concept A will require 4 iterations with a resulting anticipated cost of $300 and 20 person hours. The team will not be able to pursue this concept due to the insufficient budget to evaluate it completely. The design team is encouraged to either reevaluate the concept to see if it can be simplified to reduce iterations and save money or move on to the next best concept. This method does not include a concept ranking system but it is assumed that the design teams have completed their concept generation and performed some sort of concept scoring (such as a Pugh Chart). The method encourages designers to build as many concepts as time and money budget allow.

3.2.3 Using the Prototyping Strategy Method

The five strategy variables determined by using the prototyping strategy method have been outlined in the previous sections. The complete method is presented in Appendix E in the form given to the designer to work through. There are six primary stages to applying the method [39]:

1. Determine each of the independent design context variables for the specific design problem.
2. Order concepts. This can be based on methods like the Pugh chart [40] or other relevant methods. Note that as the strategy develops, the order may change based on the uncertainty, number of iterations, or cost of prototyping.
3. Evaluate the uncertainty of each design concept using EQ (3).
4. Estimate the number of iterations required to achieve target performance, given the uncertainty. For example, a novice engineer designing a complex micro aerial vehicle with an uncertainty, U, value of 5 will probably need about 6 iterations to complete the design, while an experienced engineer designing a bottle opener with an uncertainty, U, value of 0.2 will probably need 1 iteration only.
5. Using the provided flow charts, determine whether each iteration of each concept should include scaling, subsystem isolation, and requirement relaxation.
6. Estimate the cost, in terms of person hours and also dollars to complete each iteration of each concept, then determine which concepts to construct in parallel. The principles to this step are: (a) that the highest ranked concepts should be considered first, (b) as many concepts should be included as possible, (c) but a concept should not be pursued if the estimated cost of pursuing that concept exceeds available budget (i.e. the cost of all iterations).

Once the designer works through the method and determines the five strategy variables, they are tabulated into an over-all strategy which the designer can follow.

Figure 8 shows an example prototyping strategy write-up [38]. The predicted strategy is not a finalized plan that must be followed until the end, but rather it is a guide for upcoming prototypes. The method must be revisited after each iteration to evaluate if the strategy should be changed.

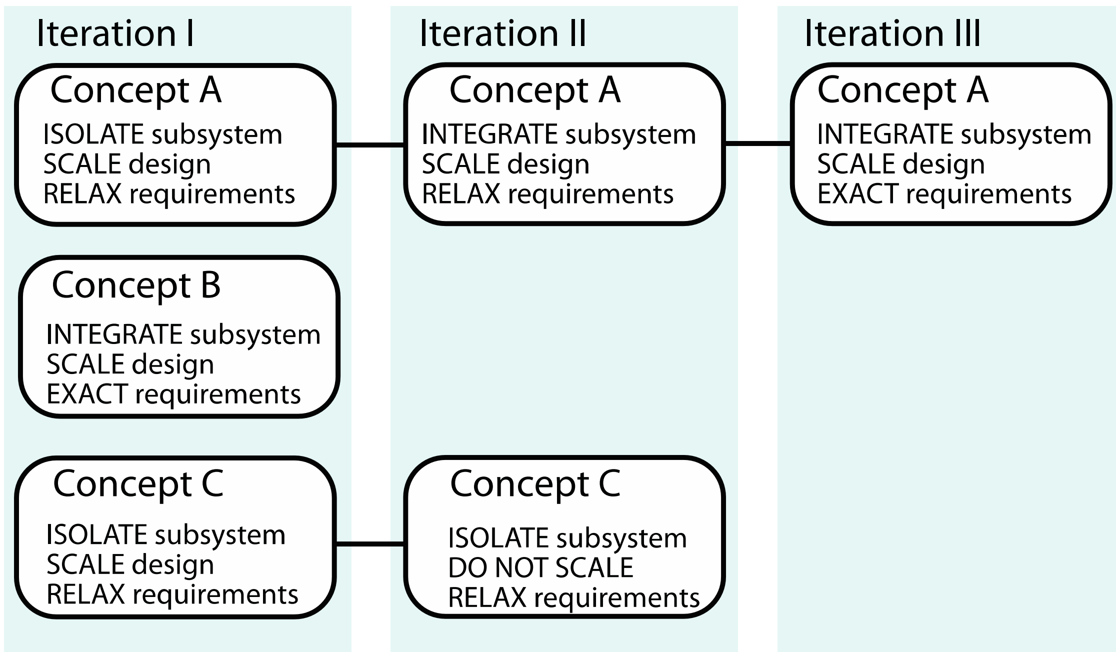


Figure 8. Example Prototyping Strategy Write-up

3.3. Experimental Assessment of the Method

The prototyping strategy method was evaluated in two experimental settings. We first implemented the method in senior capstone design courses at The University of Texas at Austin, Texas A&M University, and the United States Air Force Academy. The students were grouped into multi-disciplinary teams that worked on a wide range of industry sponsored design problems. We evaluated the quantitative impact the method had on the teams' prototyping strategy and the qualitative value it provided.

The second experimental assessment consisted of a controlled experiment that focused on the explicit use of the method and the effect it had on overall prototype performance. Those who used the method were compared to a control group who did not receive the method or any kind of prototyping instruction.

3.3.1 Capstone Design Course Implementation and Assessment

We implemented the prototyping strategy method in three senior engineering design courses to evaluate its effectiveness among design teams working on real design problems. In particular we desired to answer the following questions:

1. Does exposure to the method cause a designer or design team to change their prototyping plan?
2. Do participants react positively to the method and do they apply the method?
3. Is there a positive correlation between adhering to the method and effectiveness of the prototyping strategy taken?

The experimental setup consisted of three simple and straightforward surveys. The first survey was issued prior to the teams receiving the method. This survey inquired of their anticipated prototyping strategy and served as a baseline for comparison. The second survey guided the teams through the prototyping strategy method and had them create a new prototyping strategy. The teams were then left with their strategy to complete their prototyping and testing process. At the close of the semester, when the projects were completed, we issued the students a third survey which asked them to report on the effectiveness of their chosen prototyping approach and how closely their executed process matched the process indicated by the method. The answers to these questions were given on a Likert 1-10 scale.

From the three surveys given we aggregated the data below, which answers the corresponding research questions indicated previously [39]:

1) The change between the pre-method (1st survey) and post-method (2nd survey) strategies that participants describe.
2) Assessment of the method.
   a. How closely the participants followed the method (Likert scale of 1-10).
   b. How valuable the participants found the method to be (Likert scale of 1-10).
3) The value of the method in guiding the team towards a successful prototyping effort.
   a. Overall effectiveness of the executed prototyping strategy (Likert scale response).
   b. Effectiveness of effort in terms of staying within budget (yes or no responses).
   c. Effectiveness of effort in terms of having sufficient build time (yes or no responses).

3.3.2 Capstone Design Course – Results

There were twelve design teams from three universities who participated in this experiment. Each team's design problem was unique as were their prototyping strategies. As mentioned previously the data was collected through three surveys: (1) before seeing the method; (2) after seeing the method but before prototyping; and (3) after prototyping.

For the metric "change between the pre-method (1st survey) and post-method (2nd survey) strategies" we counted the choice elements of each of the surveys and noted the changes induced by the method. For instance the choice to scale a prototype is considered one element. As another example, suppose one team prior to receiving the method had planned to scale the second iteration of their first concept, but then after receiving the method they decided to instead build a full scale model of the second iteration of their first concept. This would be recorded as one change induced by the method. The number of elements and changes was measured and averaged across all participants. These results are summarized in Table 9 [39]. The average change, 8.9 elements, between pre- and post- method strategy across all participants has a significance of more than one standard error. There was no significant trend, towards or away from scaling, subsystem isolation or requirement relaxation or even in the total number of prototypes planned [39].

Table 9. Changes to strategy from introducing method

Average number of elements	Standard error	Average number of changes	Standard error
16.21	1.50	8.90	1.29
Average number of prototypes: before	Standard error	Average number of prototypes: after	Standard error
6	0.98	6.22	1.02
Average number of prototypes to be scaled: before	Standard error	Average number of prototypes to be scaled: after	Standard error
1.37	0.23	1	0.16
Average number of prototypes to be functionally isolated: before	Standard error	Average number of prototypes to be functionally isolated: after	Standard error
1.60	0.26	1.66	0.27
Average number of prototypes with relaxed requirements: before	Standard error	Average number of prototypes with relaxed requirements: after	Standard error
1.60	0.26	1.37	0.23

Table 10 shows the percent of those who followed the method versus those who did not. Here we define those who “followed the method” as anyone who reported the degree with which they followed the method equal to or greater than five on the Likert scale. Ten means that they followed the method exactly. We then used this grouping of method followers verses those who took a different approach to evaluate use of time/budget (Table 11) and perceived overall prototyping effectiveness (Table 12).

Table 10. Assessment of method on Likert scale

	Mean	Standard error	Percent of individuals
Assessment of method by individuals who followed method	7.4	0.29	61%
Assessment of method by individuals who used a different approach	2.3	0.56	39%

Table 11 shows that statistically significantly more of those who followed the method reported to have had sufficient time as opposed to those who diverged from the method. Table 12 also shows that those who followed the method felt their prototyping efforts to be more effective than those who did not adhere to the method (10 means the approach was very effective).

Table 11. Sufficiency of time to build and budget to build

	Had sufficient time	Had sufficient budget	Percent of individuals
Followed the method	57% said yes	79% said yes	64%
Diverged from the method	25% said yes	75% said yes	36%
***p* - value**	0.07	0.42	

Table 12. Correlation between effectiveness of prototyping effort and following the method

	Mean	Standard error	Percentage of individuals
Overall effectiveness of prototyping process - those who followed the method	7.9	0.28	64%
Overall effectiveness of prototyping process - those who used a different approach	6.0	0.82	36%

In summary, the results from the capstone design course experiment reveal three important conclusions: (1) the prototyping strategy method has a great impact on initial prototype planning when compared to not using the method; (2) those who use the method feel more positive about the prototyping approach; and (3) when design teams use the prototyping method the more effectively allocate their budget and time.

3.3.3 CONTROLLED STUDY

Our second approach to experimentally evaluating the prototyping strategy method consisted of a controlled study. Forty engineering students were paired into teams of two and divided into two sets of 10 teams: (1) control, which did not receive the prototyping strategy method and (2) experimental, which were instructed in the use of the method.

Both control and experimental groups were given the same amount of time, materials, working environment, and design problem. The engineering problem given to the students (shown in Figure 9 [38]) was specifically designed to be solved in approximately 3 hours. The objective was to create a device to move a coin (a US quarter) to a target without using any human energy during the release. Since the purpose of this experiment is to evaluate prototyping and not concept generation we provided generalized design concepts for teams to base their prototyping upon. This was meant to eliminate noise from teams generating more creative concepts and increase their focus towards prototyping.

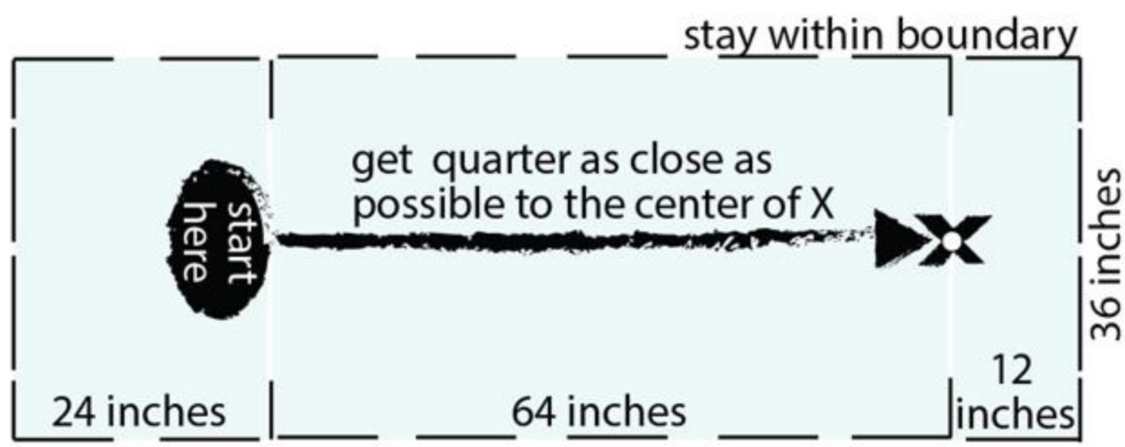


Figure 9. Controlled Study Design Problem

Through this experiment we desired to answer the following research questions:

1. What effect did the method have upon performance of the resulting design (prototype)?
2. Self-assessed success of the prototyping strategy for experimental and control group, in terms of.
   a. Effectiveness: Was the prototyping approach successful overall?
   b. Sufficient Time: Was the prototype finished in time?
   c. Sufficient Materials: Were there sufficient materials?

The first research question is critical in objectively evaluating the effectiveness of the method in improving design team performance. We planned to measure the effectiveness by comparing the performance of the experimental and control groups. The second research objective was answered by gathering student perceptions through Likert based surveys.

At the end of the three hour prototyping session all teams were instructed to stop working on their prototypes and prepare for final evaluations. The researchers then went to each team and watched as they deployed their final prototype. When the device came to rest the distance from the center of the X to the center of the coin was measured. Teams were given three tries and we compared the best of their three attempts.

3.3.4 Controlled Study Results

The main performance metric measured in this experiment was the final position of the coin after the teams deployed their prototypes. The results were categorized as binary hit or miss. A "hit" was scored when the coin came to rest within 3 coin diameters of the center of the X; those that fell outside this zone were considered a "miss".

As displayed in Table 13, the results indicate that 10 out of the 10 experimental teams "hit" the target while only seven out of nine control teams achieved this target performance. Using a two-tailed t-test, this corresponds to a P = 0.016, indicating that the experimental group performed statistically significantly better than the control group.

Table 13. Controlled Experiment Results

Measured Performance Results					
	Experimental		Control		Significance
Percent Teams Within 3*$D_{quarter}$	100%		78%		$p = 0.016$
Designers' Self-Assessed Results					
Effectiveness	$\bar{X} = 7.61$	$\sigma = 1.74$	$\bar{X} = 8.4$	$\sigma = 1.29$	$p = 0.26$
Sufficient Materials	90.1%		100%		$p = 0.03$
Sufficient Time	76%		93%		$p = 0.06$

Table 13 also shows the results gathered from the self-assessment survey. Interestingly, despite the measured performance difference between experimental and control groups there was not a significance difference in perceived effectiveness. One possible explanation for this could be that the prototyping strategy method is non-intuitive and leads designers outside their comfort zone. In contrast, as discussed previously, when we implemented this method in the capstone design, course students who followed the method indicated greater self-perceived prototyping effectiveness.

As expected, the results did not show the method to have an advantage in students perception of their use of time and materials. This is because both the experimental and control groups had sufficient time to complete the design challenge (the experiment was specifically design and implemented so they would). Furthermore, the method prompts the designers to expend their time and resources in order to achieve greatest success (as opposed to settling for the first solution developed). The data specifically supports this, as 60% of experimental teams built two or more concepts, while only 30% of control teams did likewise. Therefore, when self-assessing their prototyping efforts, experimental teams were more likely to feel like they did not have sufficient time and materials to complete their prototypes because they initially planned to expend their resources, resulting in more effective prototypes.

3.4. Prototyping Strategy Method Conclusions

The previous sections review the development, implementation, and assessment of our first prototyping strategy method. Overall the method was well received. The experimental results indicated that the method helped teams perform better, use their time and resources more effectively, and consider prototyping strategies they otherwise would not have.

However, feedback from the students who used the method indicated that the prototyping strategy method is cumbersome. Estimating the variables and working the equations is not as straightforward, time-efficient, and intuitive as desired. We still felt the underlying principles captured by the method were true and fostered success, but we wanted to capture those same principles and present them in a simplified, intuitive, and streamlined approach. Taking a cue from our own strategy, we iterated on the prototype development method. Much of the foundational research and heuristics, as outlined above, remained the same, but I will briefly review how they apply to the new method. For clarification to distinguish from the original or first prototyping strategy method I will refer to the new method as the "prototyping strategy guide" or PSG for short.

3.5. Heuristics Based Prototyping Strategy Guide

As discussed above our original prototyping strategy method gathers information about independent design context variables and uses a series of equations, flowcharts, and questions to determine values (or choices) for dependent prototyping strategy variables, such as the number of prototypes to build, prototype scaling, and subsystem isolation. The dependent strategy variables were derived from prototyping heuristics outlined by Moe [36], Christie [37], and Viswanathan [26].

Although the method proved to be effective it was also cumbersome and not intuitive. As we set out to redesign the method we decided to take the approach of making a "guide". To explain the difference, our original method is like a machine. It is programed to provide certain outputs for given inputs. Whereas, a guide is more like a teacher. It provides the principles that have been tried and tested, prompts designers to ask themselves the difficult but pertinent questions, and ultimately leaves the engineering to the engineers.

The process of transforming a design concept into a virtual or physical prototype is a fine science that is dependent upon the specific circumstances of a design problem. It takes a great deal of planning, coordinating, and decision making to bring a product to life. Our prototyping strategy guide (PSG) assists designers to develop a strategy for their early stage prototypes. It serves as a communication tool for the design team to mull over and work out together. After working through the guide designers and their teams will be able to formulate a clear vision of what their first set of prototypes will be.

3.6. PSG Overview

We intend the PSG to be a generalized tool that can be used by a variety of types of design teams, but with the infinite number of design problems, catering to everyone's needs is difficult. Therefore, prior to developing the PSG we first clearly outlined the scope and assumptions for this research. Table 14 shows our intended scope and the list below outlines our assumptions:

- Prior to developing a strategy, concepts have already been generated and evaluated based upon design criteria (e.g., a Pugh Chart).
- This method is only for early stage (verification type) prototypes.
- Prior to using the method the user has basic knowledge of engineering concepts, such as iterations, scaling, subsystems, design requirements, etc.
- The guide prepares teams for ONE build of a prototype(s). Before proceeding to subsequent iterations the designers are advised to rework the strategy guide based upon the knowledge they gained.

Table 14. Scope of the Prototype Strategy Guide

	Primary	Secondary	Not within current scope
Dependent	# of concepts # of iterations Parallel vs. series Subsystem isolation Scaling Physical vs. Virtual/Analytical Relax design requirements	Time/Financial constraints	Manufacturing types Materials Man power allocation In-house vs. outsource work Budget breakdown for each prototype
Independent	Time Budget Uncertainty	Error/Accuracy Define purpose of prototype	

As noted in Table 14, not only are we setting out to simplify the previous method but we have also added the decision of creating a "Physical vs. Virtual/Analytical" prototype as a dependent design variable.

3.6.1 HEURISTICS

Similar to our original method we have incorporated the heuristics outlined by Moe [36], Christie [37], and Viswanathan [26]. In the guide we present these at the very beginning. As the designers consider these best practices at the onset they will be better able to incorporate them into the strategy they create. Below is a summary of the heuristics presented in the guide:

- Successful teams often initially prototype three or more different concepts.
- Prototype early and often. Consider low-resolution prototypes to explore many concepts quickly and economically.
- Keep prototypes as simple as possible while yielding the needed information, thereby saving time and money.
- Allocate adequate time to the engineering process for building and testing.
- Prototyping and engineering analysis need to work together for maximum effectiveness.

3.6.2 STRATEGY VARIABLES

The PSG helps designers consider six main strategy variables: *(1) How many concepts should be prototyped? (2) How many iterations of a 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?* These are not the only decisions designers will encounter but we have determined these to be most critical success and are applicable to most design problems.

To guide designers to make these decisions we have created Likert-scale decision matrices to translate context variables into prototyping strategy decisions. Each of the strategy variables is defined below, the supporting research is summarized, and their corresponding decision matrices are presented. The complete PSG can be found in Appendix F.

Number of design concepts in parallel

Parallel prototyping occurs when two or more fundamentally different concepts are built simultaneously to achieve the same end functionality. Conversely, in serial prototyping one prototype is built and followed by another (e.g., competitive prototyping by sub-groups at a design firm). Research studies have shown that when design teams pursue multiple design concepts in parallel there is an increase in performance of the final prototype [35, 31]. Furthermore, Dahn and Mendelson [28] investigated how parallel concept testing effects profit distribution (uncertainty), cost of testing, and total budget. They found that parallel concepts allowed designers to quickly explore the breadth of the design space. They endorse parallel concepts but present an optimal model to determine the number of concepts to purse (i.e. profit uncertainty divided by the cost per test) [41].

We have incorporated these research findings into the prompts of our Likert-scale decision matrix while still allowing the designers to consider their experiential knowledge. Figure 10 shows the "Number of Concepts" decision matrix as presented in the guide.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	There are sufficient materials to prototype multiple concepts.					
B)	There is sufficient time to prototype multiple concepts.					
C)	Pugh rankings are close enough that multiple concepts show promise.					
	Use the sum of your responses to the above questions to determine whether a single or multiple concept(s) will be pursued (e.g., a positive sum would suggest pursuing multiple concepts).	One concept ←			Multiple concepts →	

Figure 10. Number of Concepts Decision Matrix

If the design team chooses to pursue multiple concepts they are instructed to decide as a team which concepts to pursue. Since this guide is helping teams determine their prototyping strategy for one iteration, all the chosen concepts will be prototyped simultaneously in the upcoming iteration. The guide will need to be revisited and a new prototyping strategy needs to be set forth for subsequent iterations.

Number of iterations

Building a prototype, testing and evaluating the prototype, refining the design concept, and re-building another prototype of that same concept is called “iterating” (e.g. the progression from initial to final form models for a car body design). Empirical studies have determined that pursuing iteration [35] correlates with increased performance outcome in the final prototype. We also adapt the theoretical findings of Thomke & Bell, [29, 30] who use an uncertainty minimization approach to determine the number of iterations to develop. Thomke and Bell conclude that savings could be achieved through multiple low fidelity prototypes, which is also supported by the empirical research [29, 30]. Finally Dahan and Mendelson conclude that iterations succeed when cost is constrained as iteration is lower cost that parallel testing [28]. The strategy encourages the designer to explore multiple iterations when feasible. To help designers determine the number of iterations to pursue the guide provides the matrix shown in Figure 11.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
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.					
	Use the sum of your responses to the above questions to determine whether a single or multiple iterations will be pursued (e.g., a positive sum would suggest pursuing multiple iterations).	Do Not Iterate ←				Iterate →

Figure 11. Number of Iterations Decision Matrix

Scaling

Prototype size can be either larger or smaller than the planned final design size; however, with scaling the prototype retains relative characteristics of the full-size form (e.g.. a Navy ship built to 1/100 scale for initial water-tunnel testing). Previous empirical research studies found that when a full-system model is very costly, time consuming or impractical to build for verification purposes as a prototype, a scaled prototype can be very useful for testing the system [27]. This may also be true when a full-size system is feasible, but a scaled model is much lower in cost and allows rapid iterations. Figure 12 shows the "Scaling Decision Matrix" from the PSG.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	A known scaling law(s) will permit accurate knowledge to be gained by looking at a scaled model of the system?					
B)	Scaling will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to scale the design (e.g., a positive sum would suggest scaling the prototype).	Do not scale ←			Scale the design →	

Figure 12. Scaling Decision Matrix

Subsystem isolation

Often a subsystem of a design concept can be prototyped and evaluated in isolation (e.g., testing of LCD components, without casing, for a monitor design project). The empirical research identifies that a prototype may embody a subsystem or the full system [27]. The indications for pursuing a subsystem are similar to those for scaling. When it is relatively difficult to construct the full system and a designer is confident that sufficient information is obtainable from building and testing an isolated subsystem, a subsystem prototype can be used. Particularly, subsystem isolation is useful when it allows rapid cycles of build and test for a complex subsystem. To assist designers in the decision to isolate of integrate subsystems we have created the following decision matrix (Figure 13):

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	The interfaces between the subsystems are predictable and/or are NOT critical.					
B)	1 or 2 subsystems embody critical design requirements that will likely need iteration.					
C)	Prototyping a subsystem will significantly reduce time, cost or complexity compared to full system prototyping.					
D)	Can an isolated subsystem be properly tested?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to isolate or integrate subsystems (e.g., a positive sum would suggest isolating subsystems).	← Integrate Subsystems			Isolate Subsystems →	

Figure 13. Sub-system Isolation Decision Matrix

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). Prototypes may or may not meet the final design requirements [27]. By carefully constructing a test that may not meet full system requirements, but does in fact capture some critical aspects of system function, the designer can determine potential benefits or drawbacks of a design without investing an unnecessary amount of effort or resources to the build. Figure 14 depicts the decision matrix used to guide designers in determining if they should relax the design requirements during prototyping.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	The flexibility of the design requirements is such that they can be relaxed during prototyping and meaningful results can still be obtained?					
B)	Requirement relaxation will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to relax the design requirements (e.g., a positive sum would suggest scaling the prototype).	Do not relax ←			Relax the design requirments →	

Figure 14. Design Requirement Relaxation Decision Matrix

Physical vs. Virtual Models

A physical prototype is a tangible, material model of a product or subsystem, whereas 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). Previous studies [26, 27] also identify that a prototype may be either physical or virtual. In a recent publication, [42] we also find that virtual prototypes are beneficial when the cost of a virtual prototype is lower and allows for more rapid iteration. To assist designers in determining if they should build a physical or virtual model the PSG provides a decision matrix as depicted in Figure 15.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	Virtual prototype(s) will require less time than building physical prototype(s).					
B)	Virtual prototyping will be sufficiently accurate to model critical physics, or interfaces and/or help evaluate critical design requirements.					
C)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.					
D)	There is sufficient time & budget to construct both virtual & physical prototypes.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical			Virtual →	

Figure 15. Virtual vs. Physical Prototype Decision Matrix

3.6.3 Using the Decision Matrices

Figure 10 through Figure 15 above contain the six multi-point prompts of the prototype strategy guide. Each strategy variable is determined by averaging the Likert response to the multi-point prompts. Completing this process can drastically alter a designer's proposed prototyping strategy. For example, one of the teams in the in-class study (discussed below) was designing a material corrosion prevention system and used the planning tool to formulate their prototyping strategy. Prior to using the tool they identified two concepts that appeared to be promising: (1) an impressed current and sacrificial anode monitoring system, and (2) a four-point anode monitoring system. As they reviewed the matrix in Figure 10, they found that there was enough material to build multiple design concepts, two concepts showed promise, and each would be quick to build. Therefore they decided to pursue construction of both of these design concepts, an idea that previously was not considered.

As can be seen in the decision matrices, the method is designed to allow consideration of the designer's experience with strategic research-based heuristics. This addresses the fact that material and time allotments are not always explicit or pre-determined and allows for human discretion in these choices, while at the same time providing a guide based on known best practices.

3.7. Experimental Assessment of the Method

We assessed the new tool in two environments: (1) a controlled experiment in which volunteers completed a prototyping design challenge, and (2) an open-ended capstone design class with a variety of sponsored design projects. In both cases students received training and employed the newly created prototyping strategy formation tool. We chose these testing environments to remain consistent with testing our original prototyping strategy method (discussed above) and provide a common ground for comparison between the two iterations of this tool.

3.7.1 Controlled Study Experiment

In this experiment 64 students from a senior level mechanical engineering design class at The University of Texas at Austin were divided into 32 two-person teams. The teams were split equally into control and experimental groups. Our previous research indicated that many designers do not consciously consider the prototyping strategy variables we introduce; therefore, the control is defined as the group solving the same design problem in the same allotment of time and resources, but without access to the strategy decision matrices.

The design problem prompted teams to build a freestanding triggered device to propel an 8.5x11 inch sheet of paper the farthest distance with the greatest amount of repeatability. Students were instructed to maximize the objective function:

$$\mathrm{Score} = \mathrm{Dist}_{\mathrm{AVG}} - 2 * (\mathrm{Dist}_{\mathrm{MAX}} - \mathrm{Dist}_{\mathrm{MIN}}) \qquad \text{EQ. (6)}$$

Although our analysis weights distance and repeatability in various ways, this objective equation clearly guided teams to maximize distance while minimizing variance. The design criteria also specified a minimum score of 25 feet to successfully complete the design challenge. This design problem was chosen because it can be solved in two hours of prototyping time, prototyping efforts are tractable, and there are multiple possible design solutions.

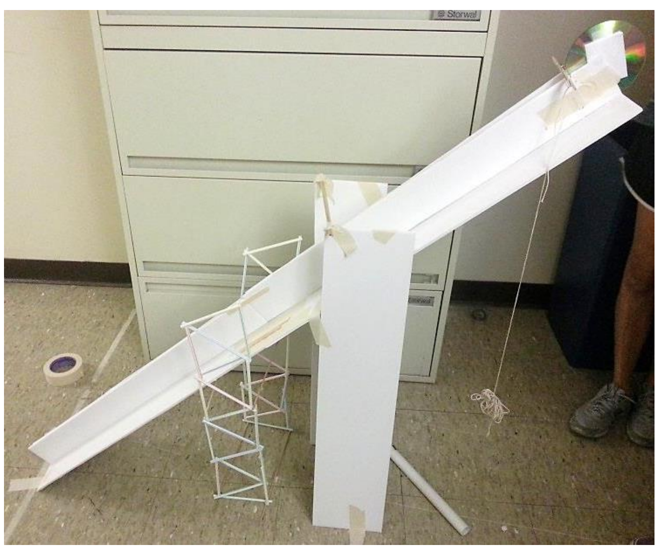


Figure 16. Example solution to the given design problem.

To simplify the experiment and reduce the noise induced by concept generation, we provided the teams with four rudimentary design concept sketches to base their prototyping upon: (A) sling shot, (B) wheeled vehicle, (C) rolling cylinder, (D) catapult. Figure 16 depicts an example of one solution a team designed, using concept C, to successfully complete the challenge. All teams kept a running log of time spent testing, concept tested, design change made since previous test, and distance reached. At the end of the two-hour prototyping period, each team made five launches and was evaluated by the researchers according to the three launches that gave the best performance score according to EQ. 6.

3.7.2 Controlled Study Results

Using EQ. 6 as the performance objective, the three best final launches from each team were averaged into a team score. A statistical analysis was performed using a two-tailed t-test. Figure 17 depicts the average overall performance rating for the 16 experimental and 16 control teams. The experimental group shows a higher average performance score, but not to a level of statistical significance ($p=0.43$, t-test).

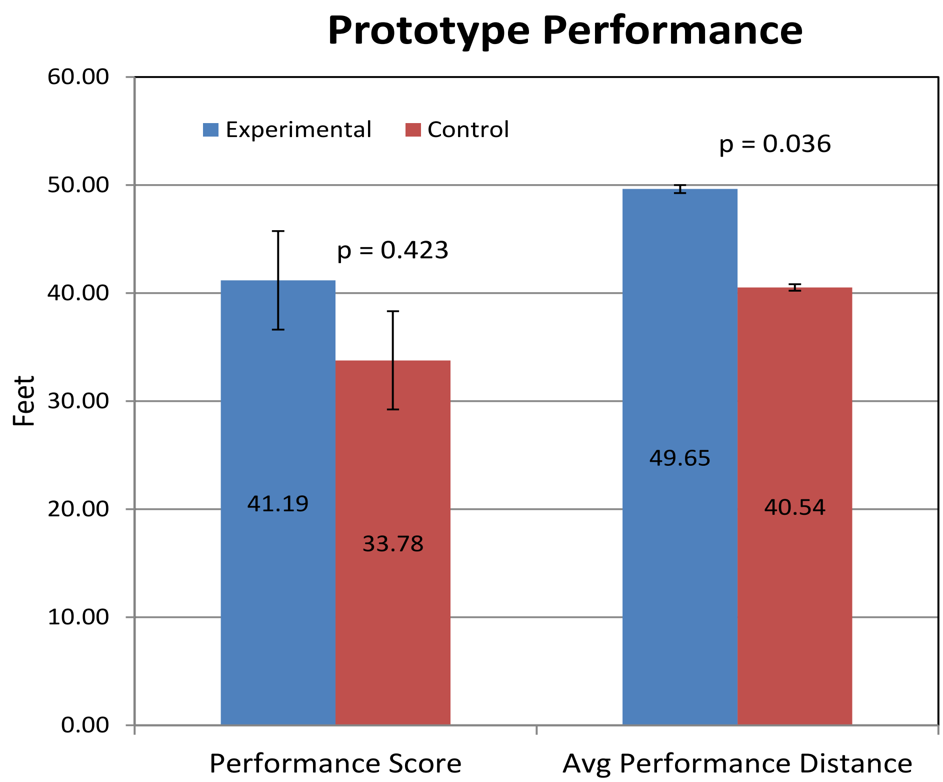


Figure 17. Comparison of Experimental and Control Groups Overall Performance

One possible explanation for this result is that this performance measure overly penalizes design variance and inherently amplifies the standard deviation. Therefore, a second metric considers only distance. In this case the performance metric was calculated by averaging all five tries from each team within the experimental and control groups respectively (Figure 17) This distance-only assessment yielded similar results to our previous evaluation, indicating the higher average of the experimental group but also proved to be statistically significant ($p = .036$, t-test).

This analysis indicates there is a performance advantage gained from the prototyping strategy formation method for this experiment. Furthermore, the data also justifies the increased performance by showing a remarkable increase in prototyping best practices such as prototyping earlier and iterating more as can be seen below. Figure 18 shows the experimental group time-to-first-prototype is dramatically lower ($p=0.03$, t-test), and Figure 19 shows the experimental group outperformed the control group at the end of one hour ($p=0.00$, t-test) by averaging distances nearly 10 feet more than the control.

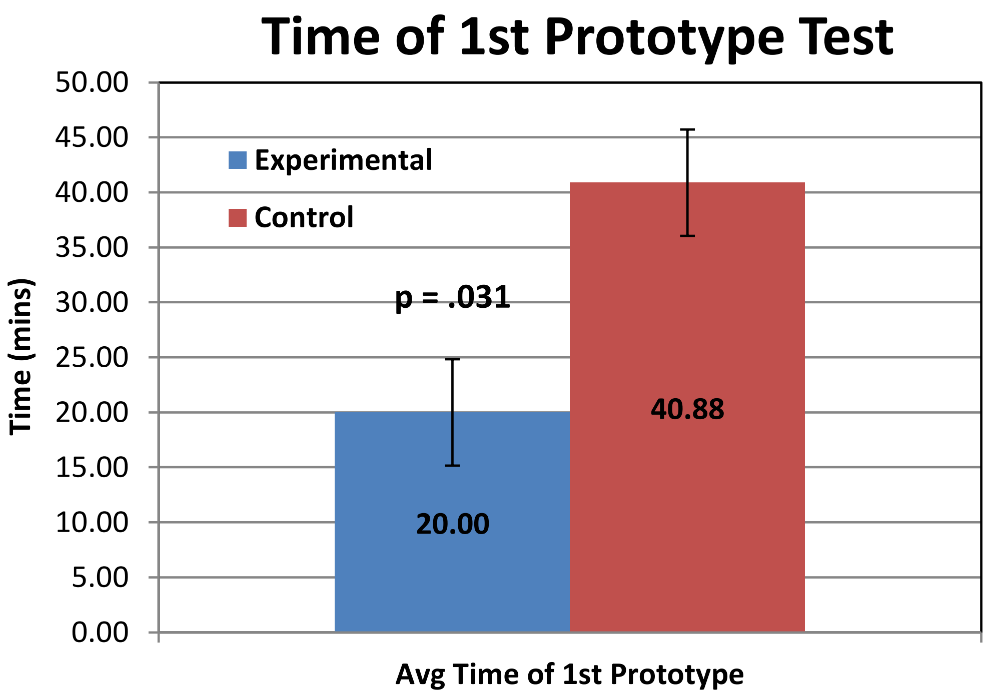


Figure 18. Average Time of First Prototype Test for Experimental and Control Groups

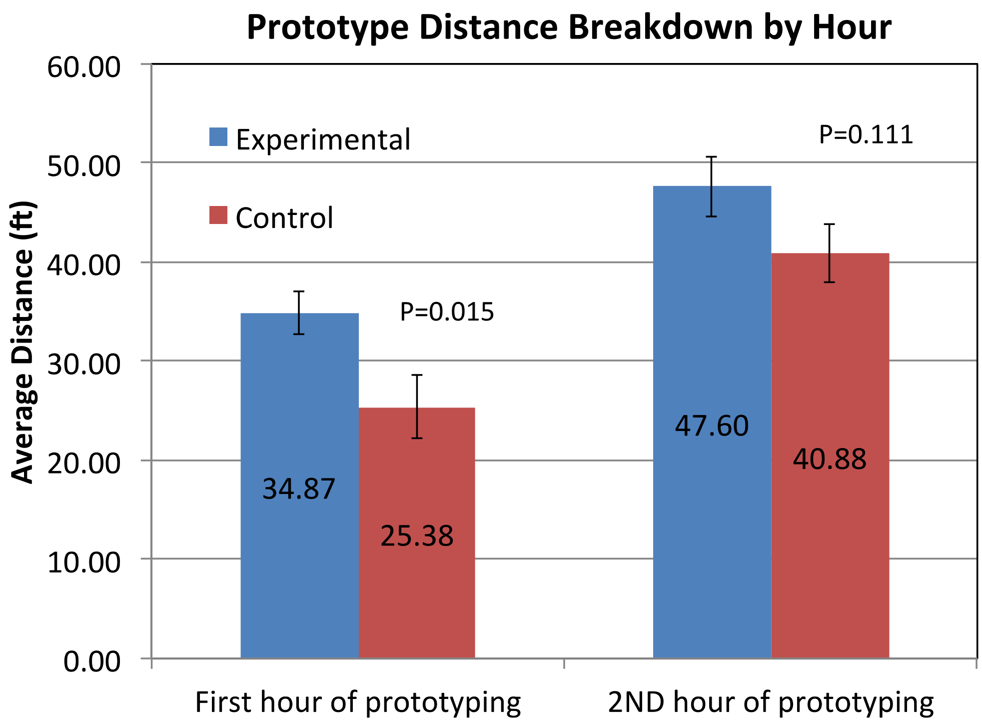


Figure 19. Average Distance Reached by Experimental and Control Groups' Prototypes for First and Second Hour.

Figure 20 further demonstrates that the experimental group achieves performance more rapidly. It can also be seen that performance for both conditions starts to level out after about an hour and a half. This indicates that the problem lent itself to a certain level of design performance saturation, and that for complex problems the strategy may be even more applicable.

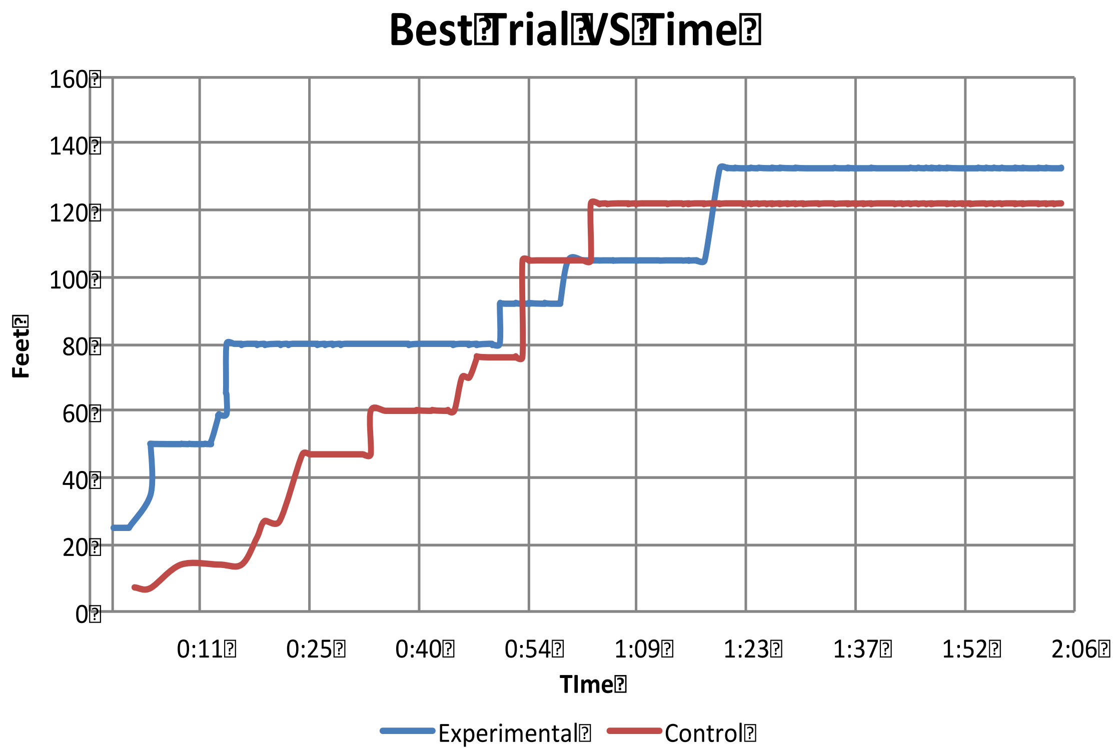


Figure 20. Best Prototype Test vs Time for Experimental and Control Groups.

Figure 21 graphically depicts how each group tested over time, and shows the experimental teams prototyped and tested at a consistent rate throughout the allotted time, suggesting better time management and better prototyping practices. The control teams were slow to begin prototyping and had to dramatically increase their efforts towards the end to finish.

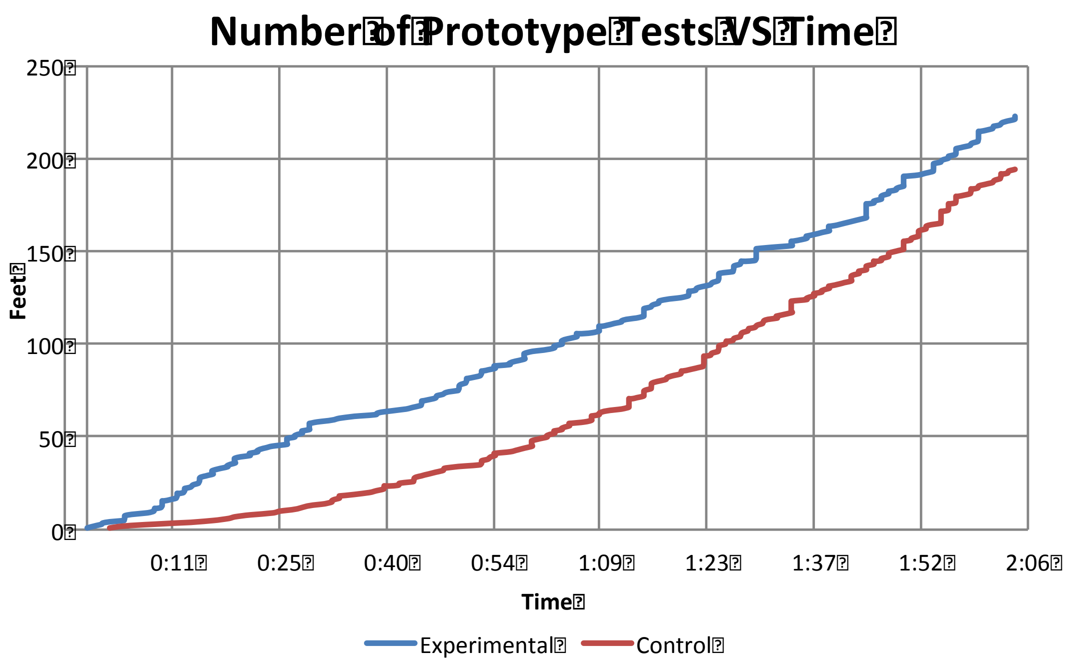


Figure 21. Cumulative Number of Prototype Tests for All Experimental and Control Groups

Figure 22 adds further insight to the observation of testing over time by depicting only tests that were prototype iterations. Here a prototype iteration is defined as a fundamental change to the physical model. The graph again shows that the control group was slow to start in the first half hour. This relatively slow progress may represent intuitive minor adjustments to their designs, rather than explicit iteration. In contrast, the experimental group was quick to start and consistently iterated throughout the experiment.

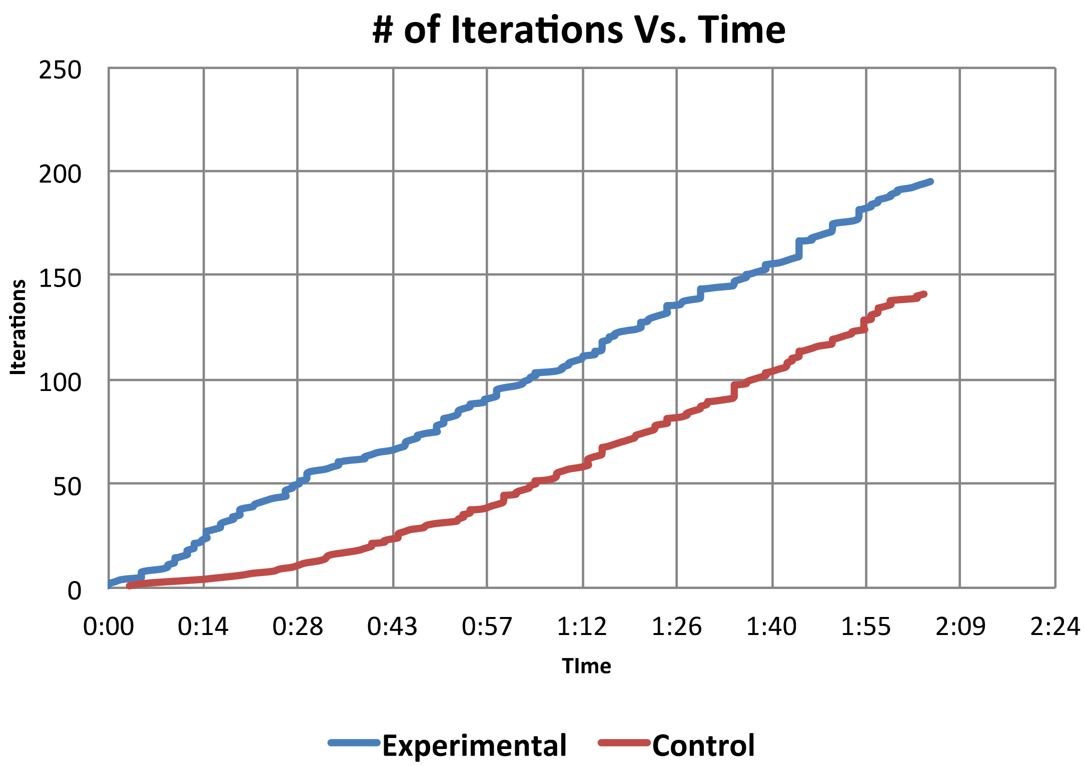


Figure 22. Number of Prototype Iterations for Experimental and Control Groups.

A post-experiment survey was administered in which teams recorded how many iterations they completed before reaching their finished product. We found that the experimental teams reported an average of 11.5 iterations for their prototypes compared to the 7 iterations for the control teams. This result represents a confidence interval greater than 95% that experimental teams completed more iterations. The more detailed prototype tracking logs showed that the experimental group had an average consistent with what they originally reported (12.31, 6.5% difference). In contrast the control group misreported their iterations by nearly 30% (see Figure 23), suggesting the experimental group showed a marked improvement in record keeping accuracy. This likely indicates that a close attention to strategy also allows for more accurate self-assessment as choices were explicit rather than intuited.

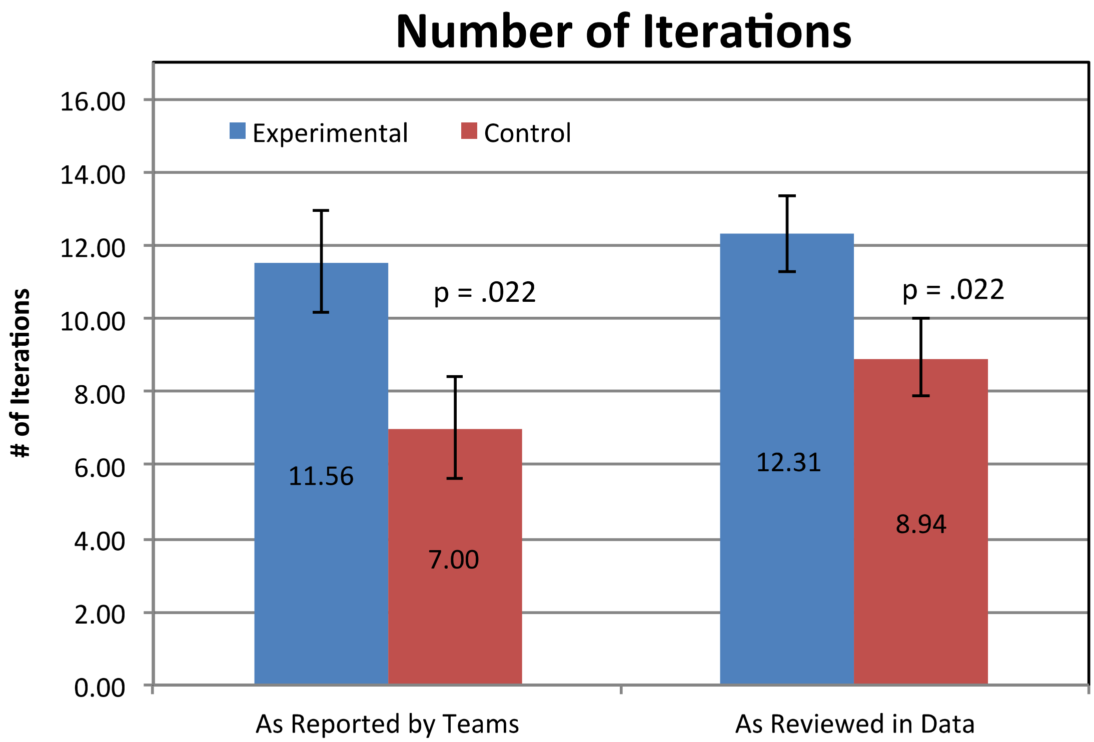


Figure 23. Comparison of Total Number of Iterations as Reported by Each Team and as Reviewed in the Data

The experimental teams were informed of the research showing successful teams often initially prototype three or more different concepts, and each experimental team did initially plan to test two or more concepts. However, only seven of the sixteen teams actually attempted more than one concept. This was more than the control group, but less than expected. Many teams that did not attempt the second concept reported their first prototype proved promising enough that they did not see the need to prototype a second concept. The prototyping strategy formation method clearly prompted teams to consider multiple concepts; however, in this particular experiment it may have been likely that teams did not have sufficient materials. This result is what would be expected from Dahan and Mendelson's experimental model [28]. Further, the performance saturation curve, Figure 20, indicates that time was not the driving constraint (for which parallel prototyping is more critical). Therefore we do not expect that this observation would recur in different design problems, as it is specific to these conditions rather than indicative of the method.

3.7.3 CAPSTONE DESIGN CLASS EXPERIMENT

Senior engineering students at the United States Air Force Academy enroll in a two semester capstone design course and work on a wide variety of corporate sponsored projects. As a part of their curriculum we introduced the method to the design teams during the Fall 2013 semester of the class. Each team then planned to implement the method once they reached the prototyping phase of their project. At the beginning of the second semester all teams had begun their prototyping. We then gathered feedback from the students and instructors to assess the usefulness of the method for formulating effective prototyping strategies.

3.7.4 CAPSTONE DESIGN CLASS EXPERIMENT RESULTS

After implementing the new tool, one student and the instructor from each of the seven teams evaluated the method on a Likert scale of 1-5 based on the following criteria: easy to follow, useful, efficient, and helped them consider aspects of prototyping they had not thought of before. As shown in Table 15, each of these criteria had an average rating of 4.0 or greater. These results validate that the methodology has a positive experiential benefit on the perception of the participant designers across a suite of design problems, team sizes and team relational dynamics. The Likert scale method is a well-established research tool in design science [39]. This section does not address technical or performance effects of the method, as discussed in section 3.2. However, it does demonstrate the integration of the strategy method into long-term multi-system projects that allow evaluation of the method on more complex design problems.

Table 15. Capstone Design Class Prototype Strategy Guide Evaluation

The prototype strategy development guide:	Avg	Stdev
...is easy to follow.	4.36	0.81
...is useful in helping my team formulate a prototyping strategy.	4.00	0.85
...helped my team consider aspects of prototyping that would have otherwise been overlooked.	4.00	0.85
...is an efficient tool for formalizing a prototyping strategy.	4.00	0.76
...is an important part of the design process.	4.57	0.62
Likert scale: 1 (completely disagree) - 5 (completely agree), Sample size: N=14		

Along with these positive responses to the method, we also received invaluable feedback to improve the method, including:

- We should clarify whether the strategy must be followed strictly or is re-workable after initial efforts.
- The generalizability of the criteria should be further explored.
- Alternate orders for the strategy should be considered.

3.8. Future Research

Results from both the controlled and capstone studies are encouraging. Future research should consider several additions as well as attempts to address the feedback. These may be guided by the following questions:

1. Implementation of a prototyping effort often appears to be a very multi-faceted and dynamic process – meaning that plans change based on new information gained at each stage of the prototyping effort. How can the method be augmented to address time-dependent context variables that influence the preferred strategy?
2. The strategy development tool (Figure 10 - Figure 15) has multiple criteria for each of the "strategy variables". What alternatives to the Likert scale averaging method may be effective?
3. Is the order of the strategy development correct? That is, can a team decide how many concepts to do in parallel before considering how many iterations may be necessary to carry out each concept?

While the current method is limited in its scope, the initial results are quite exciting and illuminating, and we aim to expand the method to include more prototyping decisions made by design teams, such as material choices (using the same materials in prototypes as planned in production), manufacturing techniques, etc.

3.9. Conclusion

This thesis reports on a newly developed heuristics-based tool that guides designers in planning a prototyping strategy based on answers to Likert-scale questions that embody empirically validated heuristics. Results from a controlled study indicate the method did improve students' performance across a number of assessment metrics. We found that teams who use the method tend to iterate earlier and more often than those that did not use the method. Furthermore, those who used the method managed their time better and were able to improve performance at a faster rate. As shown in various other experiments, these variables are directly correlated with higher success. Based upon our results we know the method enhances performance, and these additional metrics show us how.

In conjunction with the controlled study, the method was introduced to a capstone design class at the US Air Force Academy with a diverse range of open-ended sponsored design projects. The students and faculty reacted positively towards the method, indicating that it was easy to follow, useful, efficient, and helped them consider aspects of prototyping they had not thought of before.

3.10. Prototype Strategy Research Acknowledgements

This material is based in part on research sponsored by the United Sates Air Force Academy under agreement number FA7000-12-2-2005. The US Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the United States Air Force Academy or the US Government.

CHAPTER 4: MEMS HEURISTICS BASED PROTOTYPING STRATEGY GUIDE RESEARCH PROPOSAL

Previously in this thesis I have discussed the development, testing, and refinement or a prototype strategy development tool. The guide was implemented in an academic setting with students working on either corporate sponsored projects or a controlled design experiment. To some this may only show that the prototype strategy guide is applicable only with in academia. To prove otherwise I have put together a research proposal to build a case for how this prototype strategy research is applicable within one of the fastest growing industries in the world: MEMs device development.

4.1. Abstract

The MEMS components and device market is booming at an annual 18.5% compound growth rate in personal mobile devices alone [43]. Analysts are forecasting that we are on the brink of a third industrial revolution where we will see a fusion of computing, communication, and sensing. The enabler for this revolution lies in MEMS devices. The potential for MEMS devices is unprecedented and unpredictably disruptive on a global scale. Tech visionary Vijay Ullal, of Maxim Integrated Products, can foresee this $11 billion market transforming to a $1 trillion market in the next 10 years. This would entail a 54% CAGR that dwarfs the current rate of 18.5%. In order for this to be achieved Ullal proposes that the MEMS R&D speed to be increased to 15 cycles/year [44].

The research presented here will investigate MEMS prototyping methodology and techniques. This will assist researchers to more efficiently develop MEMS devices at the demanded rapid rate. Up to this point there has not been a structured guide for MEMS device prototype development. The proposed research will begin to provide a framework

of prototyping methods and techniques for design teams to take into consideration from an engineering stand point.

This research will be founded upon a literature review of best practices in MEMS device development. These findings will then be aggregated and a framework for MEMS development will be provided. The framework will consist of a set of guiding questions that will assist designers to formulize a prototyping strategy that will drive their prototyping efforts.

4.2. Introduction

According to Yole Development, a leader in MEMS market research, in 2012 the MEMS market as a whole saw a 10% growth to become a $11B business. It is expected that over the next 5 years this market will grow to $22.5B, producing 23.5 billion units [45]. Examples of MEMS device applications include inkjet printer cartridges, accelerometers, miniature robots, micro-engines, locks, inertial sensors, micro-transmissions, micro-mirrors, micro actuators, optical scanners, fluid pumps, transducers, and chemical, pressure and flow sensors [46]. Each of these components can function individually or be arranged into larger systems to sense, control, and activate micro-mechanical processes. Analysts believe MEMS devices are leading us into a third industrial revolution that fuses together computing, sensing, and communicating [44].

These systems took many years of design, prototyping, and testing to refine into the reliable components used today. What guided the designers of these systems in their development process? It is assumed they used intuition and repeated testing to answer the continual flow of questions that arise in product development. But during this process were they able to uncover some best practices of MEMS device development that could be leveraged by the MEMS research community to be more efficient in bringing new products to life?

In order to leverage the skill sets within the MEMS community a group of industry experts created a trade association called the MEMS Industry Group (MIG). They are dedicated to the advancement of MEMS devices across global markets. They recognize that there are no shared methodologies across the industry and are searching for ways to build a common language among MEMS developers. In general MEMS product development is often a collaborative effort of several independent companies spanning the value chain. This sort of collaboration can become a logistical, managerial, and communication nightmare. Without some sort of structure to manage and clearly define the collaborative engineering process teams fall short and resources are wasted.

Recognizing this need, MIG created The Technology Development Process (TDP) template which provides a framework for communicating expectations by outlining roles, responsibilities, and high level requirements of all parties involved [47]. This process is based upon the StageGate® process but has been modified for general use among MEMS device developers. The StageGate® process can be seen as an operational blueprint for effectively taking new products from idea to launch [47, pg. 3]. This developmental roadmap divides the process into a series of activities called "stages" and evaluation points called "gates". The TDP template that has been developed for the MEMS industry is shown in Figure 24.

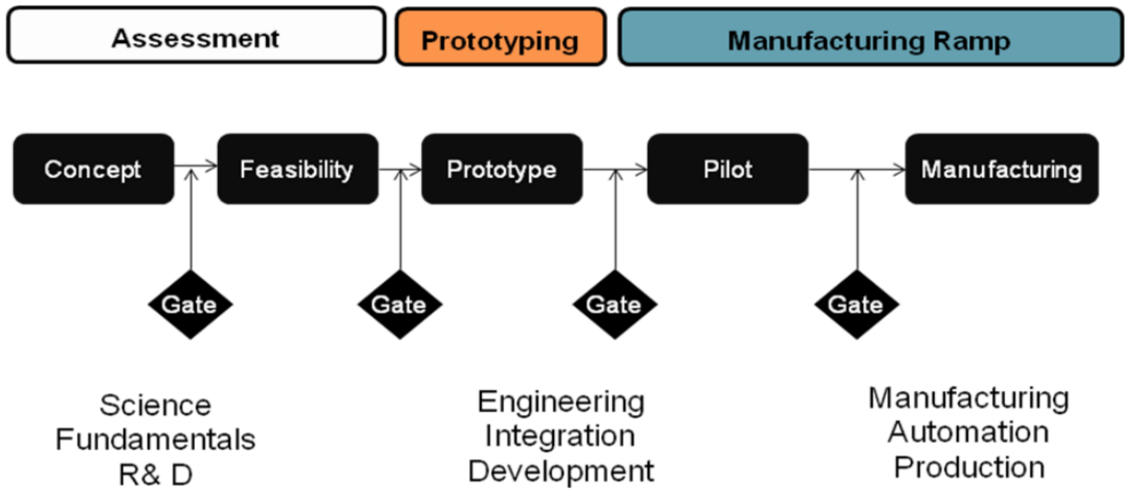


Figure 24. TDP Process Overview

The creators of TDP further laid out the development process by providing a "Protocols/Roles and Responsibilities" table, an example "Gating Requirement" table, and an example "Expanded Design Requirements" table. These tools will help teams, companies, and project managers more effectively communicate expectations and facilitate cohesion across the value chain.

Within engineering literature there is very little exploration of the methodology behind MEMS development. Currently the strategy taken is ad-hoc in nature, where the researchers proceed into development based upon past experience or internal company dictation. This research will strive to formalize the decision process of how to proceed in the MEMS prototype development process [47, pg. 6-8].

Though mentioned in the TDP Process Overview (Figure 24), this developmental framework does not provide an in-depth guide to prototyping. A prototype is an approximation of a product design concept used to refine the design and help meet customer needs. A prototype can have many forms of embodiment, such as concept sketches, low resolution models, analytical/ mathematical models, virtual modeling, component testing, process flow maps, fully functional models, etc.

The proposed research seeks to shed light on the prototyping process by providing MEMS development teams with a framework that will guide them to develop a prototyping strategy. In the next following pages is a literature search of MEMS development case studies and best practices from which a set of guiding heuristics is formulated and presented as a prototype strategy development guide.

4.3. Literature Review

Thousands of researchers have devoted their lives to the advancement of MEMS devices. As a new student in the field of study or even as a practicing engineer who is new to the industry it can be a daunting task to get a grasp on the breadth of MEMS technology. In my search for best practices I reviewed a book by Kubby [48]. This book was written as a practical guide to give engineers hands-on experience. Typically hands-on experience has been only available to well-funded universities that have cleanrooms and fabrication equipment. Kubby has brought the cleanroom to all students by guiding them through the MEMS design and fabrication process. This is done by teaching the design rules and CAD layout techniques for multi-project wafer fabrication.

Multi-project wafer (MPW) fabrication is the ideal platform for those learning MEMS development because many of these processes have well-established design rules that separate designers from fabrication challenges. In addition to simplicity, these processes allow fabrication masks and wafers to be shared by multiple designers, which greatly reduces the production cost and thus enables students and engineers alike to realize their designs without direct access to a cleanroom.

One company that offers MPW services is The Mosis Service (Marina del Rey, CA). Their “shared mask” model can combine a vast array of designs from multiple customers, or even from a single company, onto one mask set. This opens a practical prototyping avenue for designers to test and debug their designs prior to making substantial strategic investments [49]. They offer a variety of fabrication processes with varying feature size capabilities. Table 16 shows a list of processes they use.

Table 16. Standardized Manufacturing Processes Offered by Mosis [49]

Vendor	Process	Feature Size	Minimum Size[1] (mm²)	Number of Parts In A Lot
ON Semi	C5 (CMOS)	0.5 µm	5	40
	I2T100 (CMOS)	0.7 µm	10	20
	I2T30 (CMOS)		8	
	I3T80 (CMOS)	0.35 µm	10	20
	I3T50 (CMOS)			
	I3T25 (CMOS)			
AMS	C35 (CMOS)	0.35 µm	4	25
	H35 (HV CMOS)			
	S35 (SiGe BiCMOS)			
IBM	5HPE (SiGe BiCMOS)	0.35 µm	25	40
	5PAe (SiGe BiCMOS)			
	7RF (Mixed Mode)	0.18 µm	25	40
	7WL (SiGe BiCMOS)			
	8RF-DM/LM	0.13 µm	25	40
	8HP (SiGe BiCMOS)			
	8WL (SiGe BiCMOS)			
TSMC	CL035, CM035 (CMOS)	0.35 µm	25	40
	CL025 (Logic)	0.25 µm	25	40
	CM025 (Mixed Mode)			
	CL018 (Logic)	0.18 µm	25	40
	CM018 (Mixed Mode)			
	CL013G (Logic)	0.13 µm	25	40
	CR013G (Mixed Mode)			

These processes are considered to be well-established standards with set layer thicknesses; therefore, this approach to prototyping could be design limiting. But by using this method a design can be validated quickly at a low cost.

In the MEMS literature there are relatively few works that focus specifically on best practices and formalized strategies for MEMS device development. In fact, Engineering Times reported that MEMS best practices vary from vendor to vendor and that each claims the best way to be "my way" [50]. In order to gain insight to the methodology I have searched for MEMS device case studies to extract heuristics from seasoned MEMS designers.

One case study I reviewed was sponsored by the European Space Agency and covered the design, prototyping, and testing of a low cost MEMS rate sensor [51]. A team of engineers was commissioned to design a rate sensor that was not only low cost but offered the same level of performance and space environment compatibility as competing technology. Their successful approach to this task evolved into a MEMS rate sensor development program.

The team first delved into this challenge by searching for existing off-the-shelf technology as the basis for their design. They identified a very successful BAE Systems automotive silicon ring resonator to serve as a solid basis for their rate sensor development (see Figure 25). This sensor would require a significant amount of innovation and development in order to meet target parameters, but as a silicon based capacitive drive/sense device it showed promise. Phase 1 of their development consisted of adjusting the off-the-shelf design and software to meet the target performance parameters. This model served as a proof-of-concept for their design and allowed them to identify the critical design attributes that affected the performance of the rate sensor.

Through benchmark testing of this device they discovered that performance was governed by the Quality factor (Q) of the resonator, the quality (mechanical) of the resonator ring, and the detector scale factor; therefore, in order to meet the performance metrics for operating in space, as quoted from their analysis, the following modifications were required [51]:

- Increasing the ring size to 8 mm from the current 4 mm.
- Increasing Q through resonator design improvements.

- Re-packaging to reduce the effects of stress coupling through the low cost automotive package.
- Using a 50 Volt high tension biasing on the detector.

Following this early stage prototyping the rate sensor team evaluated, in terms of cost and time, the feasibility of making the necessary adjustments. Since cost was one of the major drivers of the project they continually sought ways to reduce the end product cost. They discovered they were able to increase the resonator ring size to 8 mm without any change to the original production process. By using the already proven means of production, product cost and risk was reduced.

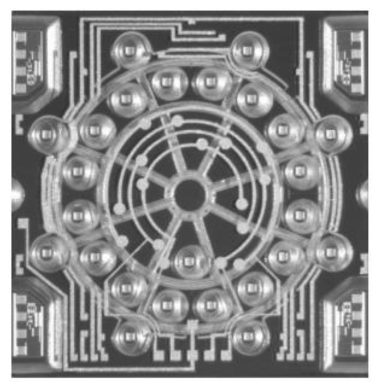


Figure 25. Capacitive MEMS Resonator (4 mm) [51]

The designers were concerned that the small output signals would cross-couple and pick up noise. To mitigate this effect they wanted to use 4 JFET (junction field effect transistor) amplifier circuits to buffer and amplify the signals as close as possible to the capacitor plates. One drawback to this plan is the JFET circuits induce the risk of potential radiation issues. In order to quickly test the feasibility of the design solution they decided to isolate and test this subsystem. They determined that it met enough of the needs and they would proceed with it as the solution with plans to further test it. Through subsystem isolation the team reduced risk and quickly made cost effective decisions. In conjunction with subsystem isolation, the team also optimized productivity through prototyping mechanical systems in parallel with the electrical components [51].

Sometimes it is not easy to mitigate risk and the only foreseeable solution is challenging. In another case study I analyzed, a design team had developed a method to prevent rotation of a MEMS sensor package that required a complicated broaching technique for manufacturing. Most companies said it was crazy and could not be done. One team attempted the challenge and proved the concept by creating a tool that broached three holes before failure. After the proof-of-concept prototype, each successive prototype brought to light a design flaw that was quickly resolved. The final tool design had a life lasting over 96,000 broaches [52].

As demonstrated here, early prototypes allow designers to figure out the physics of the system and learn what needs to be measured. Often through prototyping engineers uncover phenomena that are not inherently obvious at first. This is particularly true in MEMS development because at the micro-scale the rules change. Inertia and gravity, the macro-scale forces we intuitively understand, are no longer the dominating forces; rather, the forces and attraction between molecules govern function on the micro-scale. To this end, it is important to prototype as early as possible because it uncovers questions that were not intuitive at first.

In conjunction with building physical prototypes, another way to model and test for design feasibility is through virtual analytical tools such as finite element analysis (FEA). Due to the complexity and the inexperience of defining loads, boundary conditions, and element meshing, these tools can sometimes be misused and yield inaccurate results. This can cause teams to be skeptical of analytical models. But when performed properly the analytical models can provide accurate results along with quick design optimization. One skeptical team reported that upon design validation of a virtual vs. physical model there was over a 90% correlation between the experimental and theoretical results [52, pg. 2].

As virtual tools have improved over the years, virtual solid modeling has become a cornerstone in the product development process. A 3D geometric model provides the basis for performing more complex analyses and functions such as CNC machining, FEA, tolerance stacking, motion visualization and clearance, fluid flow dynamics, electrical simulations, equipment interfaces, rapid prototyping, etc. [53, pg. 1].

In another case study, to validate the effectiveness of virtual modeling one team built a solid model of a Silicon-On-Insulator piezoresistive pressure sensor. This virtual model was full featured, including the “wirebond pads, aluminum traces, interconnects, oxide layers and piezoresistors on the silicon membrane wafer”. Through FEA the team learned that the aluminum traces would yield under the design loads and cause sensor output errors. They also determined the necessary energy levels needed to dope the piezoresistors and transition regions. This solid model served as an open discussion conduit with the foundry that allowed the design team to receive constant feedback. Through this proficient interaction the company realized a 60% cost savings compared to going to a full service MEMS design and fabrication facility [53, pg. 2].

4.4. Proposed Research

In the previous section I explored some of the works that others have written. As can be seen there is no one single work that specifically addresses the challenges of prototyping. There are tools that help teams from a business perspective or from a general product development approach.

The research presented here aggregates some of these findings into a formalized and structure approach to creating a prototyping strategy that will guide MEMS design teams efficiently through the prototyping process. A prototyping *strategy is a set of choices that dictate the actions that will be taken to accomplish the development of prototype(s)* [36]. Below is a table outlining some decisions that a MEMS development team will face in prototyping:

Table 17. Prototyping Decisions

Physical VS Virtual	Number of concepts	Use of off the shelf components
Subsystem isolation	Parallel VS Serial	Timeline/scheduling
Relax design requirements	Scaling	Budget/resource allocation
Manufacturing processes	Process flow design	
Number of iterations	In house vs. out sourcing	

This table is neither comprehensive nor exhaustive. In order to maintain a manageable scope for this research I chose to investigate five prototyping aspects:

1. Number of concepts
2. Number of iterations
3. Subsystem isolation
4. Virtual vs. physical modeling
5. Design requirement relaxation

These five design decisions serve as a basis from which to expand this work in the future.

4.4.1 Number of Concepts

Empirical studies have shown that teams who build multiple concepts early in the design phase are more likely to succeed [54]. Due to time or budget constraints or a fixated customer, pursuing multiple concepts may not be a feasible angle to follow. Engineers can use the guide presented below to determine if their team should initially pursue one or many concepts.

Table 18. Number of Concepts Decision Matrix

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
a)	There are sufficient materials to prototype multiple concepts.					
b)	There is sufficient time to prototype multiple concepts.					
c)	Multiple concepts that show significant promise.					
	Use the sum of your responses to the above questions to determine whether a single or multiple concept(s) will be pursued (e.g., a positive sum would suggest pursuing multiple concepts).	← One concept			Multiple concepts →	

4.4.2 NUMBER OF ITERATIONS

An iteration is considered a repetition of a process or operation that yields results successively closer to the desired results. In terms of prototyping this includes building a prototype, testing and evaluating, refining the design, and rebuilding another instantiation of the concept. Determining the number of iterations is important because it allows designers to think ahead and map out (if only mentally) the design process they intend to pursue. Each iteration will serve a specific function in the refinement process and will cost time and resources.

It is difficult to determine the number of iterations that will be necessary to refine the design because it may be unclear how well the early prototypes will perform or if the concept is even feasible. To help teams estimate the number of iterations it will take to meet design requirements they should consider the following:

How many additional iterations, beyond the initial prototype, do you think will be required to meet the design requirements? To make your estimate of the number of iterations, consider the difficulty of meeting the design requirements, the difficulty of manufacturing the prototype and your level of prototyping expertise.

Designers should also consider that, as difficulty increases, more iterations may be necessary to satisfy the design requirements. These considerations will affect time and resources of the team.

4.4.3 Subsystem Isolation

Sometimes it can be beneficial to prototype individual components or subsystems. For instance, in the rate sensor case study, the design team isolated the JFET amplifier circuits from the complete assembly to test for radiation. This allowed them to quickly determine the feasibility before proceeding forward with costly and time consuming full system integration. Below is a decision matrix that will help engineers determine if they should isolate subsystems in prototyping.

Table 19. Subsystem Isolation Decision Matrix

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
a)	The interfaces between the subsystems are predictable and/or are NOT critical.					
b)	1 or 2 subsystems embody critical design requirements that will likely need iteration.					
c)	Prototyping a subsystem will significantly reduce time, cost or complexity compared to full system prototyping.					
d)	Can an isolated subsystem be properly tested?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to isolate or integrate subsystems (e.g., a positive sum would suggest isolating subsystems).	← Integrate Subsystems			Isolate Subsystems →	

The questions presented in the table will help design teams consider critical aspects of their project that may affect their prototyping decisions. Design teams can collaboratively work through the decision matrix and reach a consensus to build isolated or integrated subsystems.

4.4.4 Physical Vs. Virtual Modeling

In the literature presented above, it is evident that virtual models can be valuable to design teams. A virtual CAD model can be used for (but not limited to) FEA, tolerance stacking, motion visualization and clearance, fluid flow dynamics, electrical simulations, equipment interfaces, process optimization, etc. Within these models, designs can be modified and tested quickly. This enables rapid design optimization.

On the other hand, due to their detailed nature, virtual models can be time consuming to develop. Building a physical model may be a better solution to yield adequate results for engineers to proceed forward with their designs. Through a physical model, engineers can discover physical phenomenon that may not have been evident before. The following table is intended to assist teams balance the tradeoffs between virtual and physical modeling.

Table 20. Virtual Vs. Physical Decision Matrix

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
a)	Virtual prototype(s) will require less time than building physical prototype(s).					
b)	Virtual prototyping will be sufficiently accurate to model critical physics or interfaces and/or help evaluate critical design requirements.					
c)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.					
d)	There is sufficient time & budget to construct both virtual & physical prototypes.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical			Virtual →	

4.4.5 Design Requirement Relaxation

When designing early prototypes an engineering team can build prototypes that may not meet all the specified desire requirements. This design requirement relaxation is often used to shift focus to fundamental functions and not get hung up on stringent requirements. Of course, in the end all design requirements must be met, but early relaxation may help with proof-of-concept modeling and refinement. Below is a decision matrix that will help teams assess if design requirement relaxation is a good technique to use in their prototyping strategy.

Table 21. Design Requirement Relaxation Decision Matrix

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
a)	The flexibility of the design requirements is such that they can be relaxed during prototyping and meaningful results can still be obtained?					
b)	Requirement relaxation will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to relax the design requirements (e.g., a positive sum would suggest scaling the prototype).	Do not relax ←			Relax the design requirments →	

4.4.6 Aggregated Heuristics

Prototyping is often a means to mitigate risk. In the previous sections I presented decision matrices that will guide MEMS development teams to formulate a prototyping strategy. The decisions presented here are not all inclusive but serve as a starting point. During the literature review I gathered a few best practices (or heuristics) that design teams should consider when formulating a course of action for prototyping.

- Prototype early and often. Consider low-resolution prototypes to explore many concepts quickly and economically [36].
- Use proven means of manufacturing to reduce the risk and cost of manufacturing [48, 51].

- Use off-the-shelf components where possible. These components have been thoroughly tested and remove unnecessary development [51].
- Successful teams often initially prototype multiple concepts [54].
- Keep prototypes as simple as possible while yielding the needed information, thereby saving time and money.
- Allocate adequate time to the engineering process of building and testing [47].
- Prototyping and engineering analysis need to work together for maximum effectiveness [53].
- Work closely with foundries and manufactures as they will yield valuable insights [53].

4.4.7 Using the Prototype Strategy Guide

The decision matrices and heuristics are compiled together in a functional packet and presented in the Apendix D. Teams are to use this after they have completed concept generation and evaluation but before they begin prototype. This guide will help teams develop a prototyping strategy for their *first iteration* of prototype builds. For every subsequent iteration of prototypes teams are advised to rework the guide and adjust their prototyping strategy accordingly.

The first page of the guide gives examples, definitions, and best practices. The second page has an empty prototype strategy that is to be completed by teams as they work through the guide. Pages 3-6 contain the thought provoking questions that guide teams in developing a strategy. The last page of the packet contains a worked example for the teams to reference. More importantly than the actual design of the guide itself, this guide will facilitate communication within teams which can potentially be as important as prototyping [55].

4.5. Research Methods

In order to carry out this research and test the proposed prototype strategy guide, I plan to execute a twofold experiment as follows:

1. I will issue the prototype strategy guide to MEMS device design teams at the beginning of their prototyping phase. I will have the teams fill out the strategy for their first iteration of prototypes.
2. I will then track the progress of the teams and evaluate their usage of the strategy guide. I will compare their planned prototyping strategy to their actual prototyping.

From this experiment I will be able to evaluate the usefulness of the guide by measuring:

- How many concepts did the team pursue?
- How many iterations were needed to refine the design?
- How early in the process did the team prototype?
- How closely did the team follow the prototyping strategy?
- In what ways did the team deviate from the strategy?
- Did the team use any virtual modeling? Isolate subsystems? Relax design requirements?

4.6. Expected outcomes

From the information gathered from the experiment I will be able to deduce if the prototype strategy guide helps teams develop an effective prototyping plan. The strategy guide in its current state is crude, but through tracking design teams' use of the guide valuable insights will be gained. These insights will help refine the prototype guide into a useful MEMS prototyping tool that can be leveraged by academic and industry development teams.

4.7. Future Work

MEMS devices are leading us into a third industrial revolution that fuses together computing, sensing, and communicating [44]. In order to streamline the process, designers need an engineering based structured approach to prototyping that addresses the difficult decisions they face. The research presented here is the first step in that direction. The prototype strategy guide is limited in its breadth but will serve as a basis for the MEMS community in developing a resource of prototyping best practices that can be used by all developers within the industry.

CHAPTER 5: THESIS CONCLUSION

This concludes my graduate research. In the previous 4 chapters of this thesis I discussed my research work in 1) Active Learning Modules for teaching engineering students FEA and 2) developing prototyping strategies.

This thesis has summarized the work of eight years of active learning module development. Overall our ALMs have shown to improve student performance by a normalized gain of 37.4% ($P < 0.001$). We also found that 87.5% ($P \leq 0.05$) of the implemented ALMs increased student performance. Considering that these ALMs are designed to supplement traditional lectures of engineering concepts that are typically difficult for students to understand, we find these student performance improvements to be significant.

We also found significant results in implementing our prototype strategy methodology. Results from a controlled study indicate the method did improve students' performance across a number of assessment metrics. We found that teams who use the method tend to iterate earlier and more often than those that did not use the method. Furthermore, those who used the method managed their time better and were able to improve performance at a faster rate. As shown in various other experiments, these variables are directly correlated with higher success. Based upon our results we know the method enhances performance, and these additional metrics show us how.

The goal of both the ALM and prototype strategy development research efforts is to improve engineering education. The tools and methods discussed in this thesis help solidify pertinent engineering concepts and give students hands on experience in prototyping methodology. This knowledge is applicable to a wide range of industries and will better prepare students to enter their careers.

Appendix A -Demographic survey used in ALM deployment

Improved Learning using
Finite Element Learning Modules

Thank you for taking the time to take this survey. Your answers and feedback will help teachers and researchers improve learning for undergraduate engineers nationwide.

This survey is made possible thanks to the National Science Foundation under Grant #0536197

Demographic Information

Choose your Animal ID:

Choose your institution:

Choose your learning module:

What is your major?

- Mechanical Engineering

- Electrical Engineering
- Chemical Engineering
- Bio-medical Engineering
- Civil Engineering
- Aerospace Engineering
- Computer Science
- Engineering Management
- Engineering Mechanics
- Other

Date of birth: (mm/dd/yyyy)

What is your gender?

- Male
- Female

Class:

- Freshman
- Sophomore
- Junior
- Senior
- Other, please specify

Ethnicity:

- White/Caucasian
- Hispanic/Latino
- Asian/ Pacific-Islander
- Native American Indian
- African American
- Prefer not to answer
- Other, please specify

What is your GPA?
Enter a number with two decimal points (e.g. 3.24)

Have you checked your results and completely filled every question and blank box truthfully?

- Yes
- No

MBTI Type

Instructions:

1) Follow this link to complete your MBTI personality test:

www.humanmetrics.com/cgi-win/JTypes2.asp

2. The following questions will prompt you for information from you MBTI results.

Please take the MBTI personality test and have your results ready before proceeding.

For MBTI type E/I which one is more dominate for you?

- E (Extrovert)
- I (Introvert)

What percent E/I are you? (Enter a number from 1-100 without a percentage symbol)

For MBTI type S/N which one is more dominate for you?

- S (Sensor)
- N (iNtuitor)

What percent S/N are you? (Enter a number from 1-100 without a percentage symbol)

For MBTI type T/F which one is more dominate for you?

- T (Thinker)
- F (Feeler)

.

What percent T/F are you? (Enter a number from 1-100 without a percentage symbol)

For MBTI type J/P which one is more dominate for you?

- J (Judger)
- P (Perceiver)

What percentile J/P are you? (Enter a number from 1-100 without a percentage symbol)

Index of Learning Styles (ILS)

Instructions:
1) Follow this link to complete your Interactive Learning Style (ILS) test:

www.engr.ncsu.edu/learningstyles/ilsweb.html

2) The following questions will prompt you for information from you ILS results.

Please take the ILS personality test and have your results ready before proceeding.

For ILS type ACT/REF which one is more dominate for you?

- ACT (Active)
- REF (Reflective)

What weight of ACT/REF learning style are you? Be sure to enter one these odd numbers (1,3,5,7,9,11) for the weight.

For ILS type SEN/INT which one is more dominate for you?

- SEN (Sensing)
- INT (Intuitive)

What weight of SEN/INT learning style are you? Be sure to enter one these odd numbers (1,3,5,7,9,11) for the weight.

For ILS type VIS/VRB which one is more dominate for you?

- VIS (Visual)
- VRB (Verbal)

What weight of VIS/VRB learning style are you? Be sure to enter one these odd numbers (1,3,5,7,9,11) for the weight.

For ILS type SEQ/GLO which one is more dominate for you?

- SEQ (Sequential)
- GLO (Global)

What weight of SEQ/GLO learning style are you? Be sure to enter one these odd numbers (1,3,5,7,9,11) for the weight.

Five Factor Model

Instructions:

1) Follow this link to complete your Five Factor Model (FFM) test:

www.outofservice.com/bigfive/

2. The following question will prompt you for information from you FFM results.

Please take the FFM personality test and have your results ready before proceeding.

Enter your percentile for each of the five personality traits:

Enter a number from 1 to 100 with no percentage symbol (e.g. 51)

	Openness to Experience/Intellect	Conscientiousness	Extraversion	Agreeableness	Neuroticism
Percentile					

Have you checked your results and completely filled every question and blank box truthfully?

- Yes
- No

Appendix B – ALM Administrative Notes

Preparing ALM Raw Demographic Data for SPSS

UT graduate student needs to login into Qualtrics and download the desired data: (https://utexasengr.qualtrics.com/ControlPanel/?T=1TF6OI)

Once you have the .CSV file you can began preparing the demographic data for SPSS. The following steps will guide you through the process:

1. Open the Demographic .CSV file (this is the file that we can always go back to in case the data file ever gets corrupted. Never push "Save" when this file is open because by default Excel saves it as "Unicode Text" and becomes unreadable)
2. Immediately after opening click "Save As" >> .XLS (keep the same file name)
3. There are several columns that are place holders for the survey prompts but do not contain any data. You need to delete them (highlight column, right click>>delete) in this order: BD-BB, AU-AT, AK-AJ, AA-Z, W, U, M-J, G-A
    a. If you do them out of this order the cells shift and the columns won't match up as I specified.
    b. You don't have to memorize the letters above. I just did that to directly point out the unnecessary columns. If you look at the column headings you will be able to tell which ones are not valid columns.
4. Expand column A to see the "Start Date" and delete any rows that are not from the current semester you are analyzing. (The same survey is used year after year and we do not delete the data, that way if we ever need data from a previous year it is still there.)
5. Highlight column D >> right click>> insert (this is where you will fill in the Animal Names)
6. Highlight all rows below row 2 >>Sort & Filter>>Custom Sort>>Sort By>>Column C (this makes it easier to convert the codes into Animal Names)
7. Go to DropBox and open "TEMPLATE_Module_Institution_SemYear_FinalComboDataSet.xls"
8. Immediately after opening click "Save As" >> specify location >> name the file: "Module_Institution_SemYear_FinalComboDataSet".
9. After saving click on the "Codes for SPSS Analyses" tab. The codes for the Animal Names are here
10. Going back to you Demographic data file, copy paste the Animal Names according to their respective codes.
11. In your "…_FinalComboDataSet.xls" file click on the "Ready For SPSS" tab. You will now begin to copy the data from your Demographic data file and paste it here.

12. In your demographic data file copy the Animal Names and paste them in column A of your "…_FinalComboDataSet.xls" file.
13. Skip column B for now and fill in columns C & D according to the "Codes for SPSS Analyses" tab.
14. In your demographic data file copy columns E-AI (leave out the top two rows) and paste them in your "…_FinalComboDataSet.xls" file in column E-AI.
15. Going back to column B. fill it in as "Context = combo formed from Semester, Instructor, Institution, & Module (concatenated)". This is basically the numbers in columns C-F put together in the format ######## (ex. 15020102 > Fall 2013, Brown, UoP, Bobsled)
16. Open your Raw Quiz Score file.
17. Copy the raw quiz scores and paste them in your "…_FinalComboDataSet.xls" file under the "Quiz Data (Raw)" tab.
18. Also sort the quiz scores according to Animal Names and paste them under the "Ready For SPSS" tab on the far right end of the page. (**note: when these values are pasted make sure they are pasted as static values not formulas or referenced cells. When you export this page to SPSS if there are any formulas or referenced cells they do not transfer properly and bad things happen. Follow this precious little note and it will prevent some headaches ;))
19. Update the ALM information in the "About Module" tab, "Quiz Data (Raw)" tab, and the "Results Page" tab.
20. Your file is about ready for SPSS. Go back to the "Ready For SPSS" tab and fill in all empty data cells with 999 (the code for missing data). Also inspect the data for any unusual entries. Sometimes students don't input their values correctly or Excel imports the values weird (ie percentages or dates). Do your best to interpret these and put them in the correct format.
21. Your file is now ready to be exported for SPSS analyses. Talk with Ella about how to take it from here.

Bonus note: if for some reason a file in Drop Box becomes corrupted/won't open, try renaming it. Drop box only allows certain number of characters for the file path name. Since our folder names and files have really long names we sometime over shoot the limit. Excel thinks it saves but drop box is rejecting it because the file name is too long, so the file gets stuck in limbo.

Appendix C – Example ALM Student Survey

General student feedback survey issued to students following ALM completion. Professors are given the option of customizing the survey for their specific ALM.

	Number of Student Respondents (n)					***Percentage of Valid Responses (%)***						
Survey Item	Disagree	Generally Disagree	Neutral	Generally Agree	Agree	Disagree	Generally Disagree	Neutral	Generally Agree	Agree	***M***	***SD***
1. I think that the learning module activity was intellectually stimulating.												
2. I think that the learning module activity was challenging.												
3. The learning module software was easy to use.												
4. I enjoyed the FEA learning module.												
5. The learning module activity assisted me in understanding the course content.												
6. The format of the learning module does NOT need improvement.												
7. The organization of the learning module does NOT need improvement.												
8. I understand the course topic covered in this learning module activity.												
9. Personally witnessing and developing the finite element models in these activities on my own was												

better than a classroom demonstration.												
10. This approach used in this learning module was easy to understand.												
11. This approach used in this learning module is easy to use.												
12. I would consider using FEA in the future.												
13. The learning module activity assisted me in uncovering important information in engineering.												
14. I found the activity to be well organized.												
15. These activities were more effective than using class time for lecture.												
16. I identify very few, if any, mistakes in the learning module.												
17. I found the problem statement (s) to be clearly worded.												
18. I understood the learning objectives for the activity.												
19. The learning module activity steps proceeded in a logical manner.												
20. The learning module was easy to understand.												

* average student responses statistically different from "neutral" ($p \leq 0.05$)

Student responses to short answer questions were as follows:

41. How might the learning module activity be improved? Please be specific.
42. Prior to the learning module activity, did you have knowledge of FEA software?

	Number of Responses
Yes	
No	

43. Previous exposure to FEA influenced my performance.

	Number of Responses
Not At All	
Insignificant Influence	
Minor Influence	
Some Influence	
Extensive Influence	

44. Prior to the learning module activity, were the example problem(s) covered in class or in textbook readings?

	Number of Responses
Yes	
No	

45. Previous exposure to the problem(s) or solutions influenced my performance.

	Number of Responses
Not At All	
Insignificant Influence	

Minor Influence	
Some Influence	
Extensive Influence	

46. List three adjectives that best describe the learning module.

Positive attributes	Negative attributes	Neutral

Appendix D – Combined ALM Data

FE Learning Module	Semester	Students (N)	Pre-Quiz Avg (%)	Post-Quiz Avg (%)	Grade Improvement	% Student Improvement	Normalized Gain	Statistically Significant Improvement (for group as a whole)	Statistically Significant Subgroup Differences Found based on MBTI or ILS preferences?	Student Reaction based on Survey Responses**
Specific Absorption Rate	Fall 2006	20	63.8	81.5	17.7	27.74	48.90	N/A	N/A	N/A
Curved Beam	Fall 2006	9	71.1	82.2	11.1	15.61	38.41	Yes	N/A	N/A
Biomedical Electromagnetics	Fall 2006	6	62.9	76.7	13.8	21.94	37.20	N/A	N/A	N/A
Steady-state Heat Transfer in a Bar	Spring 2007	19	50	72.9	22.9	45.80	45.80	Yes	N/A	N/A
Transient Heat Conduction in a L-Bar	Spring 2007	19	62.9	72.9	10	15.90	26.95	Yes	N/A	N/A
Bolt and Plate Stiffness	Spring 2007	12	55.8	65	9.2	16.49	20.81	Yes	N/A	N/A

Lateral Frequency of aCantilever Beam	Fall 2007/Tuskege e	7	63.1	79.6	16.5	26.15	44.72	Yes	N/A	N/A
Bio Electromagnetic s	Fall 2007/UOP	8	57.1	80	22.9	40.11	53.38	N/A	N/A	N/A
Lateral Vibration of a Tapered Cantilever Beam	Fall 2007	16	63.1	72.3	9.2	14.58	24.93	yes, P=.000	No	N/A
Cylinder Drag	Fall 2007	7	49.9	77.1	27.2	54.51	54.29	N/A	N/A	N/A
Friction Flow in a Pipe	Fall 2007	7	58	77.1	19.1	32.93	45.48	N/A	N/A	N/A
Transmission Parameters of Infinitely Long Co-axial Cable	Fall 2007	10	42.5	67.5	25	58.82	43.48	N/A	N/A	N/A
Curved Beam	Fall 2007/UOP	16	52.75	66.31	13.56	25.71	28.70	Yes	N/A	N/A
Probe Feed Patch Antenna	Spring 2008	10	60	81.3	21.3	35.50	53.25	N/A	N/A	N/A
Curved Beam	Fall 2008/UOP	13	61.1	74.6	13.5	22.09	34.70	Yes	N/A	N/A

Cantilever Beam	Fall 2008/Tuskege e U.	5	43.4	63.6	20.2	46.54	35.69	Yes	N/A	N/A
Cantilever Beam	Fall 2008/UOP	15	66	74	8	12.12	23.53	Yes	N/A	N/A
L-Bracket Transient Heat Transfer	Spring 2009/UOP	14	69.86	78	8.14	11.65	27.01	Yes	N/A	N/A
Bio Electromagnetic s	Fall 2009/UOP	7	31.9	59.16	27.26	85.45	40.03	Yes	N/A	N/A
Curved Beam	Fall 2009/UOP	13	45.2	82.1	36.9	81.64	67.34	Yes	N/A	N/A
Fatigue Analysis of Rotating Shaft	Spring 2010	8	63.3	75.8	12.5	19.75	34.06	Yes	N/A	N/A
Bolt and Plate Stiffness	Spring 2010/UOP	8	66.5	74.13	7.63	11.47	22.78	Yes	N/A	N/A
Bio Electromagnetic s	Fall 2010/UOP	13	38.46	67.03	28.57	74.28	46.43	Yes	N/A	N/A
Curved Beam	Fall 2010/UOP	15	63.33	75.5	12.17	19.22	33.19	Yes	N/A	N/A

Thermal FEA: Semi Infinite Medium and Steady-State Heat Conduction	Spring 2011	11	58.3	76.5	18.2	31.22	43.65	Yes, P = .013	No	N/A
Machining Analysis During Chip Formation	Spring 2011	13	68.5	90.2	21.7	31.68	68.89	Yes, P<.001	No	Did Not Favor
Structural Analysis of Large Deformation of a Cantilever Beam	Fall 2011	16	33	35.2	2.2	6.67	3.28	No p=0.523	Introvert (N=7) > Extrovert (N=9)** (MBTI; p = 0.034)	N/A
Axisymmetric Rocket Nozzle	Fall 2011	11	42	54.5	12.5	29.76	21.55	Moderate, P = 093	Extrovert (N=5) > Introvert (N=5)** (MBTI; p = 0.014)	N/A
Small Engine Cooling Fin	Fall 2011	11	63.6	59.1	-4.5	-7.08	-12.36	No p=0.397	No	N/A
Vibration of Critical Speeds in Rotating Shafts	Fall 2011	9	62.2	72.2	10	16.08	26.46	Moderate, p = 0.067	Introvert (N=6) > Extrovert (N=3)** (MBTI; p = 0.033)	N/A

Computational Fluid Drag of Bobsled Model	Fall 2011	17	50	65.3	15.3	30.60	30.60	Yes, P<0.001	No	Generally favorable
Vibration of Critical Speeds in Rotating Shafts	Fall 2011	25	47.2	59.2	12	25.42	22.73	Yes, P=0.003	Intuitive (N=12) > Sensing (N=13)** (MBTI; p = 0.018)	Generally favorable
Machining Analysis During Chip Formation	Spring 2012	12	50.8	83.3	32.5	63.98	66.06	Yes, P<0.001	Perception (N=2) > Judgment (N=10)** (MBTI; p = 0.046)	Generally favorable
Thermal FEA: Semi Infinite Medium and Steady-State Heat Conduction	Spring 2012	26	62.5	74.7	12.2	19.52	32.53	Yes, P = 0.002	No	Generally favorable
Power Transmission Shaft Stress Analysis	Spring 2012	17	59.3	81.4	22.1	37.27	54.30	Yes, P<0.001	N/A	Generally favorable
Defibrillation Electrode Modeling	Spring 2012	18	27.1	57.6	30.5	112.55	41.84	Yes, P<.001	No	N/A

Bioelectric Field Modeling	Spring 2012	19	45.9	63.9	18	39.22	33.27	Yes, P<.002	Sequential (N=12) > Global (N=7)** (ILS; p = 0.041)	N/A
Sheet metal forming using FE Analysis: Shallow Drawing of a Circular Sheet	Spring 2012	18	50	56.7	6.7	13.40	13.40	Moderate, p = 0.083	no	Generally favorable
Curved Beam Structural	Fall 2012	36	72.2	89.4	17.2	23.82	61.87	Yes, p<.001	No	Generally favorable
Computational Fluid Drag of Bobsled Model	Fall 2012	8	48.8	72.5	23.7	48.57	46.29	Yes, p=.001	No	Generally favorable
Axisymmetric Rocket Nozzle	Fall 2012	16	42.2	67.2	25	59.24	43.25	Yes, p<.001	No	N/A
Small Engine Cooling Fin	Fall 2012	16	39.1	59.4	20.3	51.92	33.33	Yes, p<.001	No	N/A
Critical Speed of Rotating Shaft	Fall 2012	13	69.2	78.5	9.3	13.44	30.19	Yes, p = .040	No	Generally favorable

Chip Formation	Spring 2013	20	65.9	87.3	21.4	32.47	62.76	Yes, p<.001	Feeling (N=4) > Thinking (N=14) (MBTI; p = 0.114, MWp = .046) Extrovert (N=10) > Introvert (N=8) (MBTI; p = 0.034, MWp = .055)Active (N=14) > Reflective (N=4)(ILS; p = 0.024, MWp = .061)	Generally favorable
Shaft Stress	Spring 2013	31	62.1	77.7	15.6	25.12	41.16	Yes, p<.001	No	Generally favorable
Rotating Shaft	Spring 2013	31	68.1	75.8	7.7	11.31	24.14	Yes, p<.001	Judgment (N=24) > Perception (N=7)(MBTI; p = 0.045, MWp = .054)Reflective (N=9) > Active (N=22)*(ILS; p = 0.035, MWp = .064)	Generally favorable

Thermal FEA	Spring 2013	29	42	54	12	28.57	20.69	Yes, p<.001	Extrovert (N=12) > Introvert (N=14)(MBTI; p = 0.026, MWp = .041)	Generally favorable (Different survey)
Dynamics 2D Frame	Spring 2013	15	43.6	49.7	6.1	13.99	10.82	Yes, P = 0.007	No	Generally favorable
Shallow Drawing	Spring 2013	15	58.5	60.6	2.1	3.59	5.06	No, P = 0.308	No	Generally favorable
Computational Fluid Drag of Bobsled Model	Fall 2013	23	50	87.39	37.39	74.78	74.78	Yes, p<.001	No	Generally neutral
Curved Beam Structural	Fall 2013	21	62.37	88.17	25.8	41.37	68.56	Yes, p<.001	Intuitive (N=14) > Sensing (N=6)(MBTI; p = .027, MWp = .041)	No Info Received
Vibration Modes of Circular Disks	Fall 2013	12	40.83333	70.83333	30	73.47	50.70	Yes, p<.001	No	Did Not Favor
Large Deformation of a Cantilever Beam	Spring 2014	6	34.848	54.55	19.702	56.54	30.24	Yes, p = .027	No	

Two Dimensional Static and Dynamic Frame	Spring 2014	18	43.89	65.56	21.67	49.37	38.62	Yes, p<.001	No	
Machine Analysis of Chip Formation	Spring 2014	23	66.4	85.7	19.3	29.07	57.44	Yes, p<.001	No	
Number of modules implemented		**Total number of Students**	**Average Pre**	**Average Post**	**Average Point Increase**	**Average % Improvement**	**Average Normalized Gain**	**Normalized Gain T-Test**		
55		833	54.41	71.46	17.05	31.35	37.41	P < 0.001		

Appendix E - Prototype Strategy Method

Design Context Variables

Variable	Definition	Example	Your Project
Budget ($\$_A$)	This is the allocation, in dollars, for developing prototypes for the project.	$200	
Time (T_A)	This is the total amount of time allocated to prototyping, measured in man hours.	210 hours (7 weeks, 6 teammates, 5 hours per week each)	
Difficulty of Requirements (D)	This variable is assigned a value for the difficulty of meeting the requirements by taking into consideration: team experience, complexity etc.	8/10 (difficult): multi-objective UAV design 3/10 (simple): gear box design	
Rigidity of Requirements (R_{eq})	This variable is a measure of the rigidity of the design requirements on a linear scale, or the stringency of the design requirements in terms of precision, quantity etc. If it is necessary that the device function within very narrow parameters, then the R_{eq} value is high.	7/10 (very rigid): a formula SAE racer 2/10 (flexible): design a human to computer interface	
Interactivity (I_{nt})	This variable is the interactivity between subsystems in the system. A high value indicates that the system cannot demonstrate function without integrating all of the subsystems.	9/10 (very integrated): a four bar linkage 3/10 (segmented): Swiss army knife	
Designer's Experience (E_x)	This is the variable to represent the designer's familiarity with designing systems like the present one.	9/10 (very experienced): 20 similar projects 1/10 (no experience): 0 similar projects	

Name:______________________ Team: __________________________

Procedure for Development of Prototyping Strategy:

Note: ( ) means "if applicable"

	Method	Example	Results			
1	Complete the design context sheet	$\$_A$, T_A, D, R_{eq}, I_{nb}, E_x				
2	Examine design concepts and order them - select the top concepts, up to five. For steps 3-8 evaluate the first concept only.	1. Concept A (Best) 2. Concept B 3. Concept C 4. Concept D 5. Concept E	1. (2.) (3.) (4.) (5.)			
3	Evaluate the uncertainty factor (U) for this concept, using variables from step 1, where: $U = \frac{\left(\frac{R_{eq}+D}{2}\right)}{E_x}$	$U_A = 2$	Concept 1: (Concept 2:) (Concept 3:) (Concept 4:) (Concept 5:)			
	Note: the degree to which U is greater than one represents the amount of UN-certainty. i.e. U = 10 is very uncertain					
4	Given the uncertainty factor and your best intuition, evaluate the number of iterations (I_t) which you believe will be needed to ensure the prototype meets the design requirements	e.g. $\#I_t = 3$	$\#I_t$ of concept 1: ($\#I_t$ of concept 2:) ($\#I_t$ of concept 3:) ($\#I_t$ of concept 4:) ($\#I_t$ of concept 5:)			
	Iteration is defined as: sequential attempts at prototyping					
5	Estimate the necessary resources (in person hours) to implement each iteration of the concept (C_t)	Concept 1: Iteration i = 20 hrs Iteration ii = 10 hrs Iteration iii = 5 hrs	1 it. i _______ (2 it. i _______) (3 it. i _______) (4 it. i _______) (5 it. i _______)	(1 it. ii _______) (2 it. ii _______) (3 it. ii _______) (4 it. ii _______) (5 it. ii _______)	(1 it. iii _______) (2 it. iii _______) (3 it. iii _______) (4 it. iii _______) (5 it. iii _______)	(1 it. iv _______) (2 it. iv _______) (3 it. iv _______) (4 it. iv _______) (5 it. iv _______)

6	Estimate the cost of each iteration of the concept in \$ ($C_\$$)	Concept 1:	1 it. i ______	(1 it. ii ______)	(1 it. iii ______)	(1 it. iv ______)
		Iteration i = 50\$	(2 it. i ______)	(2 it. ii ______)	(2 it. iii ______)	(2 it. iv ______)
		Iteration ii = 25\$	(3 it. i ______)	(3 it. ii ______)	(3 it. iii ______)	(3 it. iv ______)
		Iteration iii = 15\$	(4 it. i ______)	(4 it. ii ______)	(4 it. iii ______)	(4 it. iv ______)
			(5 it. i ______)	(5 it. ii ______)	(5 it. iii ______)	(5 it. iv ______)

	Method	**Example**	**Results**
7	Now evaluate the anticipated remaining budget: Remaining Time (person hours) = $T_A - \sum_{i=1}^{I_t} C_t(ith\ iteration\ of\ A)$ Remaining Budget = $\$_A - \sum_{i=1}^{I_t} C_\$(ith\ iteration\ of\ A)$	e.g. evaluating for concept A: Remaining time = 125 - (20+10+5) Remaining \$ = 300-(50+25+15) Move to concept B and evaluate cost…	After evaluating the budget and time left from concept A, continue to subtract the cost of each concept from the remaining budgets. i.e. subtract the cost of concept B from the budget that was left AFTER concept A, continue until \$ or time is exhausted.

Total cost of concept			Budget remaining, cumulative reduction (*C* = *T* - *A* -*B*-…-*N*, etc)		
Concept 1	\$ _____	t _____	Concept 1	\$ _____	t _____
(Concept 2)	\$ _____	t _____	(Concept 2)	\$ _____	t _____
(Concept 3)	\$ _____	t _____	(Concept 3)	\$ _____	t _____
(Concept 4)	\$ _____	t _____	(Concept 4)	\$ _____	t _____
(Concept 5)	\$ _____	t _____	(Concept 5)	\$ _____	t _____

8 Complete the flowcharts for Scaling, Isolation, and Relaxation for each concept for which there was budget. Complete the chart to the right for the first iteration. If time permits, fill in S.I.R. for the other iterations (on a separate sheet). Add a star '*' to the element if you think it will change between iterations

	Scaling:	Isolation:	Relaxation:
Concept 1	Y/N	Y/N	Y/N (Y/N)
Concept 2	(Y/N)	(Y/N)	(Y/N) (Y/N)
Concept 3	(Y/N)	(Y/N)	(Y/N)
Concept 4	(Y/N)	(Y/N)	
Concept 5	(Y/N)	(Y/N)	

9 Utilize this information to construct the complete prototyping strategy that includes the decisions of number or parallel concepts to be prototyped, number of iterations of each concept and the stipulation of whether or not to scale, isolate some function, or relax parameters for each concept.

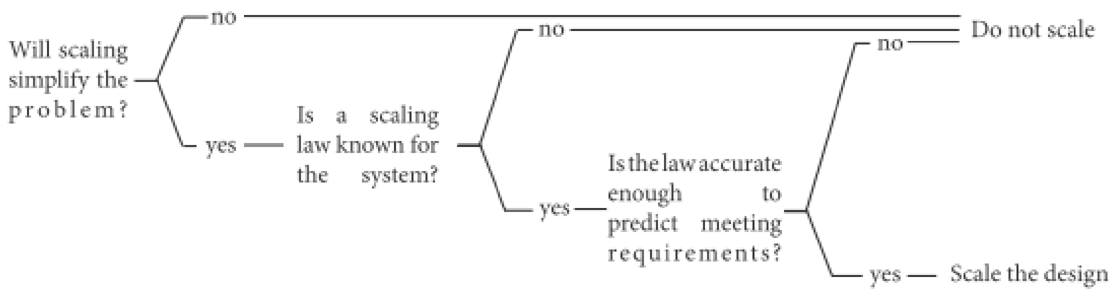
Draw out your final prototyping strategy, mimicking the example.

Prototyping Strategy Flowcharts

Scaling

Scaling is a process in which the size of the prototype is either increased or decreased. It may be applied in cases when the actual size of the device is too difficult or costly to produce or test.

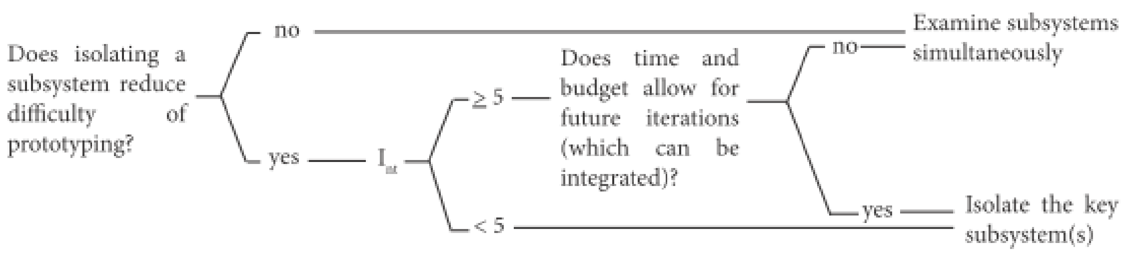
Example: A navy ship is built at ~1/100 scale the first several iterations.



Subsystem Isolation

With subsystem isolation, one of the subsystems of the device can be prototyped or experimentally evaluated while other subsystems are prototyped independently or not at all.

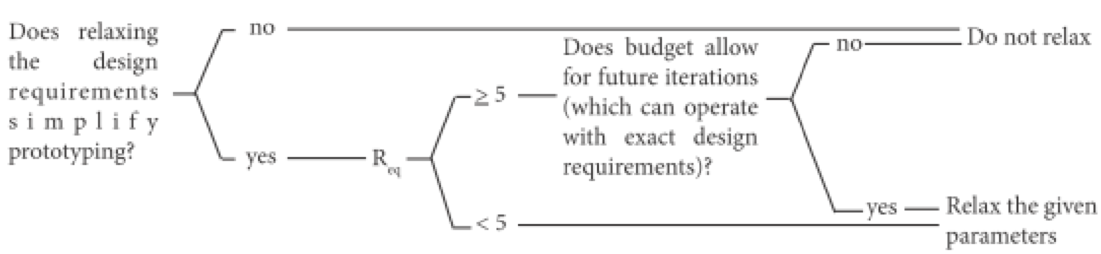
Example: Monitor design project- prototype the LCD array but ignore casing design.



Relaxation of Design Requirements

With design requirement relaxation, the values or parameters of the design can be altered to simplify prototyping.

Example: Prototype a new engine- spec it to run at ½ designated torque for the prototype.



Iteration I	Iteration II	Iteration III	Iteration IV
CONCEPT A ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT A ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT A ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT A ISOLATE: Y | N SCALE: Y | N RELAX: Y | N
CONCEPT B ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT B ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT B ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT B ISOLATE: Y | N SCALE: Y | N RELAX: Y | N
CONCEPT C ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT C ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT C ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT C ISOLATE: Y | N SCALE: Y | N RELAX: Y | N
CONCEPT D ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT D ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT D ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT D ISOLATE: Y | N SCALE: Y | N RELAX: Y | N
CONCEPT E ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT E ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT E ISOLATE: Y | N SCALE: Y | N RELAX: Y | N	CONCEPT E ISOLATE: Y | N SCALE: Y | N RELAX: Y | N

Appendix F – Prototype Strategy Guide

Use this document to formulate a prototyping strategy, and to update the strategy as prototypes are completed.

DEFINITIONS

Prototype – an approximation of a product design concept used to refine the design and help meet customer needs. A prototype can be used to embody and explore any aspect of the design using: concept sketches, low-resolution embodiment, analytical/mathematical models, virtual modeling, component testing, fully functional embodiment, etc.

> **Example:** *Prototypes of a student Formula SAE vehicle chassis might include: sketch on paper, PVC mock up, CAD model, and fully welded product. These are typically built one after the other (serial iterations.)*

Virtual Prototype - a computer based model (CAD model, motion analysis, FEA, CFD, etc.) of a product that can be used for visualization, analyzed and modified.

Physical Prototype – a tangible, physical model of a product or subsystem that can be analyzed, tested, and modified.

Subsystem Isolation – Often a subsystem of a design concept can be prototyped and evaluated in isolation.

> **Example:** *Monitor design project- prototype the LCD array but ignore casing design.*

Scaling – Prototype size is either larger or smaller than the planned final design size to reduce difficulty and/or cost, however it retains relative characteristics of the actual size form.

> **Example:** *A navy ship built 1/100 scale for initial water-tunnel testing.*

Design Requirement Relaxation – Prototypes may be built with "relaxed" design requirements to simplify the process.

> **Example:** *An initial engine prototype is made without concern for the amount of torque to save time and money while studying the basic power transfer component layout.*

Iterations – Building a prototype, testing and evaluating the prototype, refining the design concept, and re-building another prototype of that same concept is called "iterating".

Parallel vs. Serial – Parallel prototyping occurs when multiple concepts are built at the same time, unlike serial prototyping in which one prototype is followed by another. Single-lane roads allow cars to travel in serial and multi-lane roads allow cars to travel in parallel.

Prototyping Best Practices:

- ***Successful teams often initially prototype multiple different concepts.***
- ***Prototype early and often. Consider low-resolution prototypes to explore many concepts quickly and economically.***
- ***Keep prototypes as simple as possible while yielding the needed information, thereby saving time & money.***
- ***Allocate adequate time to the engineering process of building and testing.***
- ***Prototyping and engineering analysis need to work together for maximum effectiveness.***

Team Number: ____________________ Date: ________________

Prototype Strategy Template

Use this page in conjunction with the "Prototype Strategy Guide (pages 3-7)" to formulate a prototype strategy. This page provides a framework for your strategy and should be filled in as you work through the guide. The numbers in the table below correspond to the numbers on the guide.

1. Fill in the names of the concepts:	Concept 1:	Concept 2:	Concept 3:	Concept 4:
Based on criteria 1a-c which concept(s) will you prototype first? (mark with 'X')				
2. # of iterations?				
3. Purpose of this Prototype iteration?				
4. Virtual or Physical Prototype?				
5. Isolate the Subsystems?				
6. Scale the Prototype?				
7. Relax the Design Requirements?				

Prototyping Strategy Guide

Use the guidelines below to develop a strategy. Fill in the blanks on the "Prototype Strategy" page to formalize your strategy

1. Complete the following form based on the specific aspects of your design concepts.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
1. a)	There are sufficient materials to prototype multiple concepts.					
1. b)	There is sufficient time to prototype multiple concepts.					
1. c)	Pugh rankings are close enough that multiple concepts show promise.					
	Use the sum of your responses to the above questions to determine whether a single or multiple concept(s) will be pursued (e.g., a positive sum would suggest pursuing multiple concepts).	One concept ←			→ Multiple concepts	

Based upon the table above, discuss with your team which concept(s) your team will pursue**. Mark the chosen concept(s) in the space provided in the chart on page 2.**

Prototyping Strategy Guide

Questions 2-7 will have unique answers for each concept. Accordingly, follow through the guide below for ***each chosen concept***:

> **Points to Consider**
> As difficulty increases more iterations may be necessary to satisfy the design requirements. Consider how this will affect time and resources.

2. Use the form below to determine if your prototype will require iterations. (Reference the definition/example of *prototype iterations* on pg. 1.)

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
2. a)	The difficulty of meeting the requirements will necessitate iteration.					
2. b)	The difficulty of manufacturing will necessitate iterative prototyping.					
2. c)	My team has minimal prototyping experience.					
	Use the sum of your responses to the above questions to determine whether a single or multiple iterations will be pursued (e.g., a positive sum would suggest pursuing multiple iterations).	← Do Not Iterate			Iterate →	

Based upon the chart above, will your prototype require iterations? Insert answer in the chart on page 2.

3. A prototype is often built and tested with the specific purpose of answering questions and refining the design. In the space provided in the chart on page 2, define your purpose for prototyping *this first iteration* of each *chosen* concept.

> **Points to Consider**
> Prototyping is an activity that can have many purposes e.g physics modeling, communication, or concept evaluation- consider the purpose of each build carefully.

Prototyping Study Guide

Points to Consider
For any approach that deviates from building a complete working model, be sure there is adequate time and budget for future iterations that meet all design requirements.

4. Use the form below to determine if a virtual or physical prototype will be built. (Reference the definition/example of *virtual and physical models* on pg. 1.)

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
4 a)	Virtual prototype(s) will require less time than building physical prototype(s).					
4 b)	Virtual prototyping will be sufficiently accurate to model critical physics, or interfaces and/or help evaluate critical design requirements.					
4 c)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.					
4 d)	There is sufficient time & budget to construct both virtual & physical prototypes.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical			Virtual →	

Based upon the chart above, will you build a virtual or physical prototype? Insert answer in the chart on page 2.

Prototyping Strategy Guide

5. Use the form below to determine if any subsystems will be isolated. (Reference the definition/example of *subsystem isolation* on pg. 1.)

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
5. a)	The interfaces between the subsystems are predictable and/or are NOT critical.					
5. b)	1 or 2 subsystems embody critical design requirements that will likely need iteration.					
5. c)	Prototyping a subsystem will significantly reduce time, cost or complexity compared to full system prototyping.					
5. d)	Can an isolated subsystem be properly tested?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to isolate or integrate subsystems (e.g., a positive sum would suggest isolating subsystems).	Integrate Subsystems ←			Isolate Subsystems →	

Based upon the chart above, will you isolate the subsystems? Insert answer in the chart on page 2.

Prototyping Strategy Guide

6. Use the form below to determine if the prototype will be scaled. (Reference the definition/example of *scaling* on pg. 1.)

Points to Consider
Scaling can be a function of adjusting size, loads, speeds, etc.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
6. a)	A known scaling law(s) will permit accurate knowledge to be gained by looking at a scaled model of the system?					
6. b)	Scaling will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to scale the design (e.g., a positive sum would suggest scaling the prototype).	Do not scale ←			Scale the design →	

Based upon the chart above, will you scale the prototype? Insert answer in the chart on page 2.

Prototyping Strategy Guide

7. Use the form below to determine if the prototype will have relaxed design requirements. (Reference the definition/example of *design requirement relaxation isolation* on pg. 1.)

Points to Consider
There is, to some degree, error inherit in each of the decision criteria. Consider if your formulated strategy will produce prototypes with error that would render the prototypes inadequate.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
7. a)	The flexibility of the design requirements is such that they can be relaxed during prototyping and meaningful results can still be obtained?					
7. b)	Requirement relaxation will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to relax the design requirements (e.g., a positive sum would suggest scaling the prototype).	Do not relax ←			Relax the design requirments →	

Based upon the chart above, will you relax the prototype design requirements? Insert answer in the chart on page 2.

Now that you have completed a prototyping strategy, you have a clear direction on how to proceed into the **first iteration** of your concept(s). *For every subsequent iteration it is advisable for you to rework this method and update your strategy accordingly.* This is important because with each prototype iteration you will learn new things that could alter the course of your development work.

Team Name: Prosthetic Leg

EXAMPLE

Date: ________________

Prototype Strategy (See page 2 for template)

1. Fill in the names of the ranked concepts:	**Concept 1:** *Spring Leg*	**Concept 2:** *Hinged Ankle*	**Concept 3:** *Rigid Leg*	**Concept 4:**
Based on criteria 1a-d which concept(s) will you prototype first? (X)	**X**		**X**	
2. # of iterations?	*4 more iterations (1. Manufacture and test spring, 2. Test ground interface material. 3....)*	*4 more iterations (1. CAD model new hinge and optimize for strength, 2. Build and test full feature model 3.....)*	*2 more iterations (1. Build a clean comfortable model and test, 2. Build for manufacturing)*	
3. Purpose of Prototype?	*Determine spring stiffness necessary to support user during walking*	*Use off the shelf parts to determine joint locations*	*Quick mock up to see if this is even a feasible concept in terms of body alignment and mobility.*	
4. Virtual or Physical Prototype?	*Virtual*	*Physical*	*Physical*	
5. Isolate a Subsystem?	*Isolate the subsystems (Just looking at the load bearing spring. Not concerned with connecting leg to person)*	*Integrate the subsystems (Include all subsystems)*	*Integrate the subsystems (Include all subsystems)*	
6. Scale the Prototype?	*Do not scale*	*Do not scale*	*Do not scale*	
7. Relax the Design Requirements?	*Do not relax the design requirements (Use full scale forces in CAD model)*	*Relax the design requirements (Not concerned with aesthetics or long term performance)*	*Relax the design requirements (Not concerned with comfort of attachment for this version)*	

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Vita

Brock Usher Dunlap was born and raised in Katy, Texas. Following his high school graduation in 2004 he served as a missionary for The Church of Jesus Christ of Latter-Day Saints. He spent two years serving throughout the nation of Armenia and learned the Armenian language fluently. After his missionary service he attended Brigham Young University in Provo, Utah where he studied Mechanical Engineering. During his time there he was fortunate to work on several meaningful projects. Two of these include designing humanitarian water systems for villages in Peru and building a formula hybrid race car which took first place in a collegiate international competition. Upon his graduation from BYU in 2012 Brock left Utah and returned to his homeland of Texas to attend The University of Texas at Austin as a graduate student. During his time in Austin he met his wife Katy Hemmert who was also attending UT as an accounting student. They were married December 18, 2013. Upon their graduations Brock and Katy will be moving to Michigan. Brock has accepted a position as a product development engineer at Ford Motor Company in their hybrid vehicle division.

Email: brock.dunlap@gmail.com

This thesis was typed by the author.