The influence of design problem complexity on the attainment of design skills and student perceptions

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Abstract—**One of the current educational challenges is how do we educate engineers to systematically solve open-ended real-world design problems? The capstone design course often plays a critical role in this, but there are numerous questions on how best to teach design and what are the characteristics of realistic design problems which provide excellent learning opportunities. This paper reports on a controlled evaluation of the effects of design problem complexity on students' ability to functionally abstract a design problem and its effect on their perceived value for variety of design methods. It is important for students to learn a systematic approach to the design process and to perceive its effectiveness. Students' perceptions and functional modeling skill are measured. Results, while preliminary due to limited sample size, indicate the complexity of the design problem is a critical factor in teaching design methods. There is a statistical interaction between the complexity of the design problem and opinion of functional modeling on their ability. Results also indicate that students who work on more complex design problems are more likely to expect to use functional modeling in the future. More complex design problems lead to a more positive student opinion. Further development of the functional modeling quiz is needed as is a larger sample size. Overall, results indicate that more complex design problem demonstrate to the students the effectiveness of the methods.**

Keywords- ***Design methodology; engineering education; functional modeling***

I. INTRODUCTION

The Engineer of 2020 Report recognizes that creativity, invention and innovation are indispensible qualities for an engineer [2]. These skills must be understood, developed and taught. Critical research questions exist on how engineers develop their innovation skills and how innovation can be supported. The senior capstone design course plays an important role in teaching engineering students a systematic design process to enhance their innovation skills and guide them in applying their technical knowledge to real-world problems.

Systematic method approaches to the design process, such as the ones frequently taught in capstone design courses, have been shown to improve the process by increasing designer efficiency and the quantity along with the quality of designs [3, 4]. Teaching engineering design is seen as important enough to have dedicated special sessions and conferences [5]. The capstone design experience is viewed as a critical part of the undergraduate engineering curriculum but there is little agreement on how best to teach design to undergraduates [6].

This paper explores one aspect of the capstone design course, the design problem complexity and how it influences learning and student perceptions. The complexity of a situation (design problem) has been shown to affect skill development in other domains such as accounting [7]. One critical design skill is the ability to select useful abstractions, generate them and use the results to guide their designs [8]. Functional modeling is one class of methods focused on creating abstractions of a device. A function is what the device does independent of a particular form. For example, a car battery, a flywheel and a spring, all solve the function of storing energy (a battery through a chemical reaction, a flywheel through kinetic energy and a spring through mechanical material deformation). So a functional model would represent all three in the same manner as a device that stores energy.

The complexity of the design problem may also affect students' opinions and perceptions about the various design methods taught. Students' perception may influence how well they learn a particular design skill and the choice of using a particular design method in the future is often up to the designer. The paper employs a controlled experimental comparison of teams working on a more complex design problem (a lunar rover) to teams working on a less complex problem of only a single module of the lunar rover. The following sections provide additional background on the design course and functional modeling, then describe the experimental design, the results and conclusions.

II. BACKGROUND

A. Introduction to Mechanical Engineering Design MEEN 401

MEEN 401 Introduction to Mechanical Engineering Design is a two-semester capstone design course where students work on a year-long open-ended design project [9]. The course focuses on teaching systematic approaches to systems engineering [10]. The course contains one large lecture and studio sections of approximately twenty students. All students attend the same main lecture where the various design methods are taught and includes topics such as need analysis, functional modeling, interface identification, FMEA and project planning [9]. Students learn the design methods as they apply them to their design project.

The first semester begins with each team of students working on the same design problem, for example designing a lunar rover. Students typically work in teams of three to four in a class of approximately eighty to one hundred students broken down into design studios of approximately twenty students. During the first semester, each team identifies the needs, requirements and moves through concept generation for the system level design. Approximately half way through the first semester, each studio sections selects a final system level concept and then each team within the section works on one of the sub-systems, for example the life support system. The following semester each studio selects a particular sub-system for detailed design. This course design is in contrast to less complex designs that can be completed in a year by a single team of students.

B. Functional Modeling

Functional modeling is an abstraction of a design problem which focuses on what a device does, not the specific embodiment of it. There are multiple methods for functional modeling including the FAST Method, Hierarchical Functional Models [10] and Flow-Based Functional Models in the Function and Flow Basis [1]. Fig. 1 shows a hierarchical functional model which breaks the main function of a coffee grinder, “make coffee grounds”, into smaller pieces of “input power” and “chop beans”.

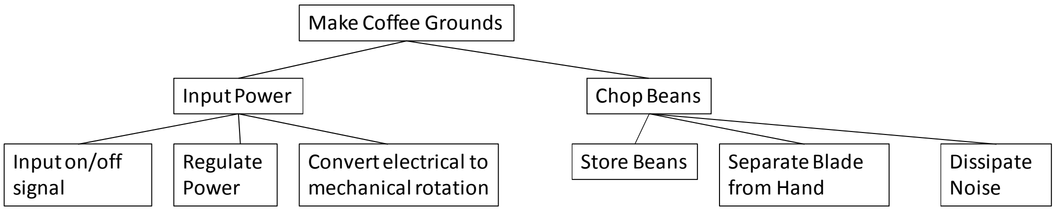


Figure 1: Hierarchical Functional Model for a Coffee Grinder

Another method for functional modeling is displayed in Fig. 2, a Flow-Based Functional Model for a Mars Rover Probe. The purpose of the probe is to break down rocks and analyze them. This functional model shows the materials, signals and energy that enter and leave the system. It also illustrations how the flows (materials, signals and energy) are changed by the functions.

The purpose of functional modeling is to focus the designer on what the device does and not on the specific form of a solution. It also reduces design fixation on a particular solution and assists with breaking down the problem into smaller pieces which can be more easily solved.

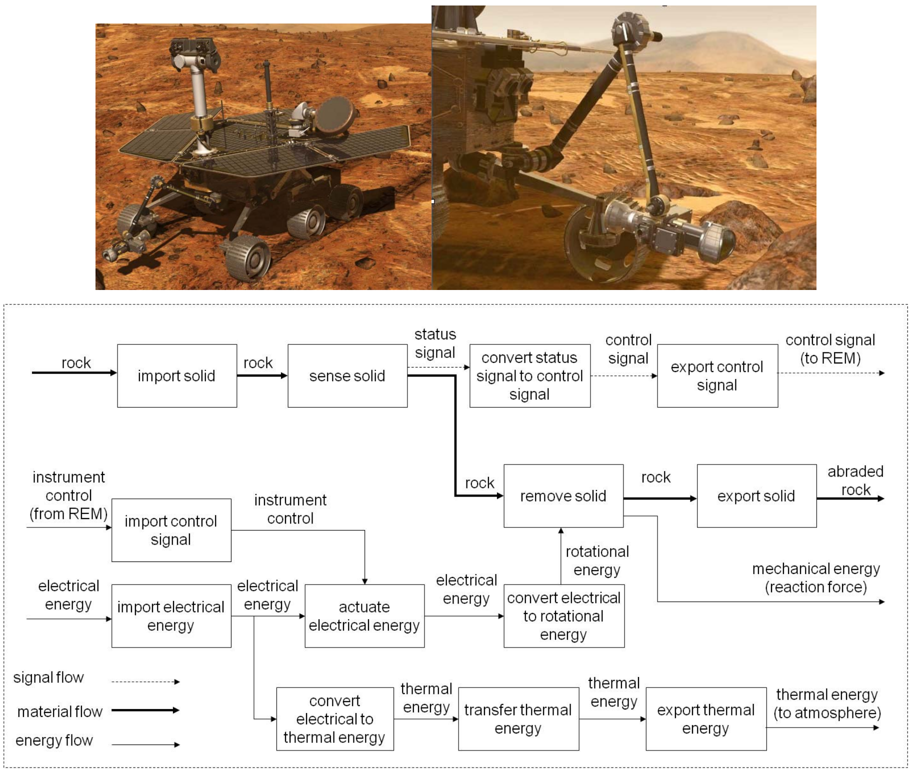


Figure 2: Flow-based functional models for a Mars Rover Probe shows how materials, signals and energy flow through a device and are acted on by the functions [1].

III. METHOD

A controlled between-subjects experiment measures how the complexity of the design problem affects student learning and perceptions of the methods. We make the following hypotheses based on the literature and discussions with experience capstone design instructors:

Hypotheses

Functional Modeling Skill Hypothesis: Students who work on a more complex design problem will achieve greater skill in functional modeling.

Student Perceptions of Functional Modeling Hypothesis: Students who work on more complex design problems will perceive functional modeling to be more valuable and are more likely to expect to use the method in the future.

Design Method Perception Hypothesis: Students who work on more complex design problems will generally perceive the design methods to be more valuable and will be more likely to expect to use them in the future.

Based on past observations it is believed that the more complex design problems such as the design of a lunar rover assist students in observing the need and impact of design methods and also provide an effective learning opportunity. It is possible that while students are learning the various design method, a more simple design problem would facilitate a deeper understanding of functional modeling.

A. Design Problems

The two design problems used to measure the effects of design complexity are (1) the more complex problem of a lunar surface vehicle and (2) the power transmission device (PTD), a module of the lunar surface vehicle. Both projects were presented to the students by an engineer at NASA who also acted as the project sponsor. The lunar surface vehicle design problem is to develop a device to aid crewmembers in exploration of the moon and transport cargo. The PTD's primary purpose is to provide mechanical power via a shaft to perform external work. Both design problems include more detailed specifications. For example for the PTD additional specifications presented at the beginning of the project included:

- shaft provides 75 horsepower at between 500-3000 rpm (variable)
- needs to be removable by crew (lightweight) with no/minimal tools
- electrical power for device provided by Rover
- extendable reach of 2 meters, capable of 500 pound lift
- swivels 360 degrees at Rover base with intermediate joint
- mechanism to be sealed with replaceable dust covers at rotating interfaces
- design to allow (not preclude) external attachment to:
    - *operate in-situ mining equipment*
    - *provide alternate power for rover movement*
    - *operate drill for recovery of soil samples*
    - *translate smaller cargo on/off Rover*
    - *play out/rewind communication/ power cables or large flexible antenna*
    - *assist in emergency translation of rover past obstacles (drive a wench/jack)*

B. Participants

A total of 64 participants were involved in the study, 48 in the Complex and 14 in the Simple Condition. Participants were recruited by offering them extra credit for filling out the method perceptions survey and their data were also correlated with a quiz which evaluated their functional modeling skill. Students were senior mechanical engineers at a large public university in the United States.

Students work in teams of three to four students. All students attend the same lecture for the design class and then are divided into design studios of 15-25 students. Each design studio has a different professor. Within each studio, one team was in the Simple Condition and the remaining teams in the Complex. Two of the Simple Teams were randomly assigned and two teams chose the Simple Condition based on very limited information about the design problem. All teams were supposed to be randomly assigned but this was not clearly communicated to the design studio instructors. The set-up of the teams allowed for the effects of the different studio instructors to be controlled.

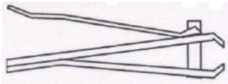
C. Measures

Two measures are used to evaluate the effects of the design problem on student learning. The first is a functional modeling ability quiz and the second is the students' opinions of the various design methods taught in class. Both measurements were made at the end of the first semester.

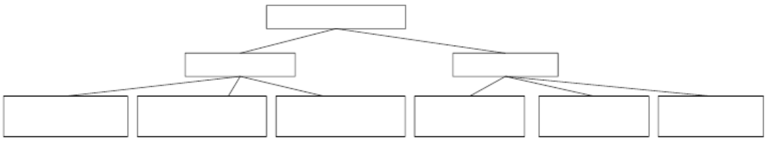
1) Functional Modeling Ability Quiz

A short quiz was created to measure the students' functional modeling ability (Sample questions in Fig. 3).

List four functions of the finger nail clipper shown.



3. Fill in the correct functions in the partial functional model for a coffee grinder from the list below.



Input on/off signal

Input Power

Separate Blade from Hand

Chop Beans

Store Beans

Convert electrical to mechanical rotation

Make Coffee Grounds

Dissipate Noise

Regulate Power

In your opinion, what is the value of each of the following for a **DESIGN PROBLEM THAT REQUIRES AN INNOVATIVE SOLUTION?**

	Zero value	A little value	Medium value	High value	Extremely valuable	Don't Remember Method
Background research / Literature review						
Need Analysis						

In your opinion, what is the **GENERAL VALUE** of each of the following for a **TYPICAL DESIGN PROBLEM?**

	Zero value	A little value	Medium value	High value	Extremely valuable	Don't Remember Method
Background research / Literature review						
Need Analysis						

Figure 1: Example questions from the functional modeling skill quiz and method perception survery.

Students were given approximately 45 minutes to complete the quiz and it was given in-class. The quiz was created by the first author for evaluating the students' functional modeling skill and this was the first time the quiz was implemented. Quizzes were scored by a teaching assistant.

D. Students Opinions of the Design Methods

A survey (Fig. 3) measured the students' opinions of the various methods listed in Table 1. For each design method, the survey measured the student's perceived value for design problems requiring an innovative solution. The survey also measured their opinions on these same methods for more typical design problems (design problems not requiring innovative solutions). The students' expected future use was also measured for each method. Perceived value and expected future use were scored on five point scales from zero value to extremely valuable (zero value, a little value, medium value, high value, extremely valuable and don't remember method) and from very unlikely to very likely (very unlikely, unlikely, neutral, likely, very likely and don't remember method), respectively. Do not remember method was included so that students' only gave their opinions for methods they remembered. Newton's Law and the Bernoulli equations are controls since it is expected that especially for Newton's law all students would see this as valuable and expect to use it in the future if they become engineers.

IV. Results and Discussion

Much of the focus of this study is on how well students learn functional modeling and their opinions of various design methods. Students who worked on more complex design problems were significantly more likely to expect to use functional modeling in the future (Fig. 4). Since the opinions are on a five point ordinal scale, Wilcoxon's Rank-Sum Test [11], a non-parametric statistical test, evaluates the statistical significance (Wilcoxon's Rank-Sum Test W_s=351.0, p=0.1 [12]). This does indicate that the complexity of the design problem does have on influence on student's perceptions of the method. As students leave the classroom environment and move into industry, it is often the designer's choice to use a particular method or not. Therefore it is important to understand students' impressions of the various methods.

Table 1: Methods [10] measured for Students' Perceived Value and Expected Future Use

Methods
Background research / Literature review
Need Analysis
Function Structure
Brainstorming
Identification of Interfaces
Failure Modes and Effects Analysis (FMEA)
Work Breakdown Structures
Drawing Trees
The general systematic approach to design taught in this class.
Newton's Law F=ma
Bernoulli's Equation

No significant difference is observed in students' functional modeling skill as a result of which condition they were in (Fig. 5). A rather small standard deviation (6.0) in quiz scores indicates that either the quiz is not doing an adequate job at evaluating students' functional modeling ability or the students' do not vary significantly in this skill (Fig. 6). There is significant range in the students' scores from 15 to 44. Further examination of the quiz results on an individual question basis and validation of the quiz is needed. Based on instructor observations the skill of the students is believed to vary substantially so a better measure of functional modeling skill is needed.

It is also likely that a students' opinion of a method could interact with how well they learn a particular method. If they do not perceive it as valuable then they might not effectively learn a method. For the current sample, an ANOVA does show an interaction between the condition and their predicted future use [Condition: F(1, 54)=0.48, p=0.19, Future Use Opinion: F(4,54)=0.58, p=0.49, Interaction: F(3,54)=2.15 p=0.1 and MSerror=24.80]. This indicates that the interaction of the students' opinion and the design problem condition they were in has a significant effect on their functional modeling ability. The sample size for students in the simple condition is currently 14 so more data are required to draw conclusions.

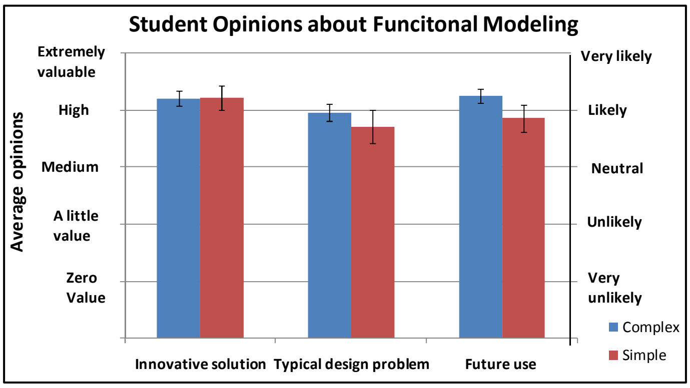


Figure 4: Students working on more complex design problems were more likely to expect to use this method in the future error bars are (+/- one standard error).

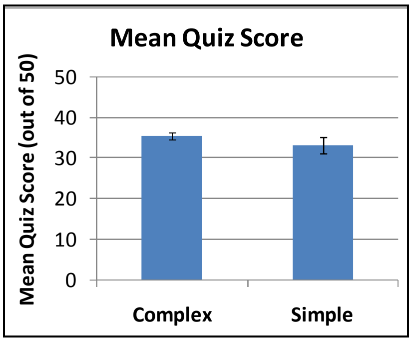


Figure 5: No statistically significant difference in quiz scores but the Complex Condition tended to be higher (error bars are +/- one standard error).

A. *General Trends In Student Opions Across the Method*

The complexity of the design problem does appear to have some influence on students' perceptions of the design methods (Fig. 7-9). Work Breakdown Structures show a consistent pattern across the three perception measures, students in the Complex Condition expect to use it more often in the future and perceive it to be of greater value than students in the simple condition. Only the perceived value for a typical design problem is statistically significant and the rest are close (future use W_s=353.5, p=0.17; innovative design problem W_s=308.5, p=0.17; typical design problem W_s=328.0 p=0.10). There is also a significant difference for expected future use of drawing trees (W_s= 254.5, p=0.03). The design methods are also generally seen as more valuable for design problems that require an innovative solution as opposed to more typical problems but there are no general trends across the design methods comparing students in the simple versus more complex design problems.

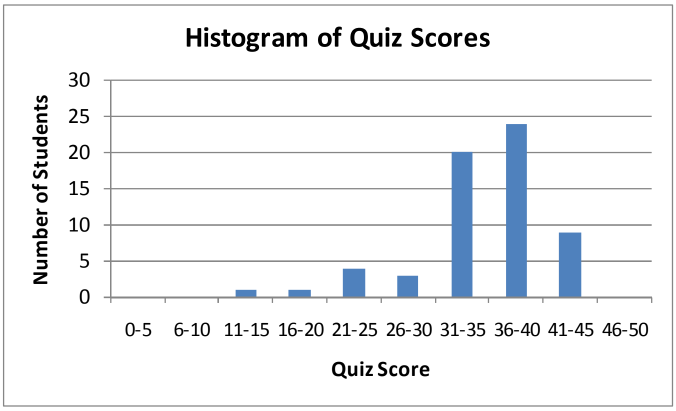


Figure 6: The scores are biased toward the high end of the scale with realively low variance (S.D.=6.0).

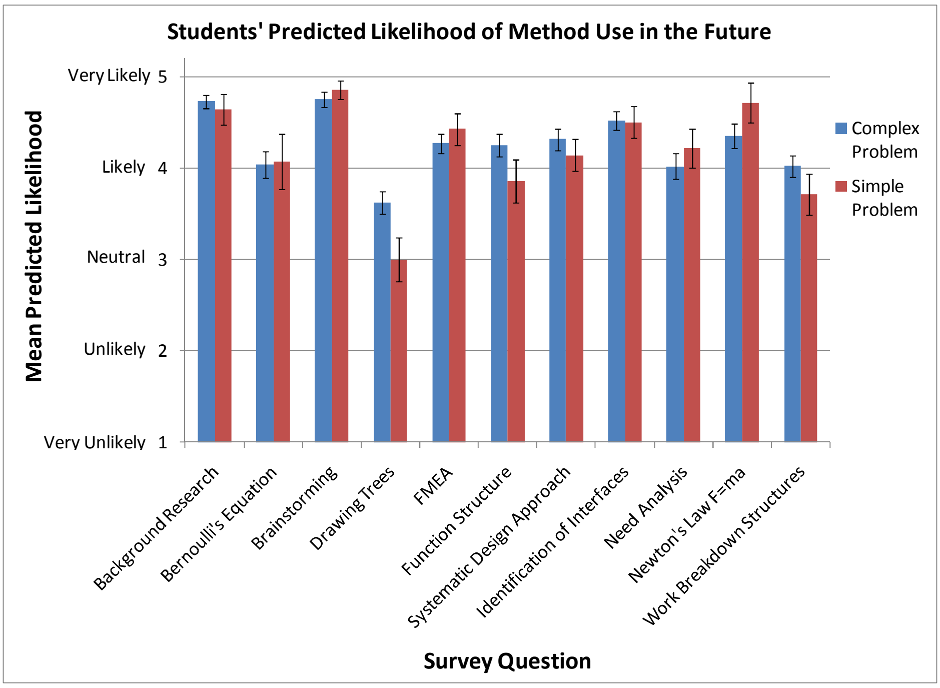


Figure 7: In general, for typical design problems, students' opinions did not vary depending on the type of design problem they had. Some methods did show statistically signifcant difference (error bars are +/- one standard error).

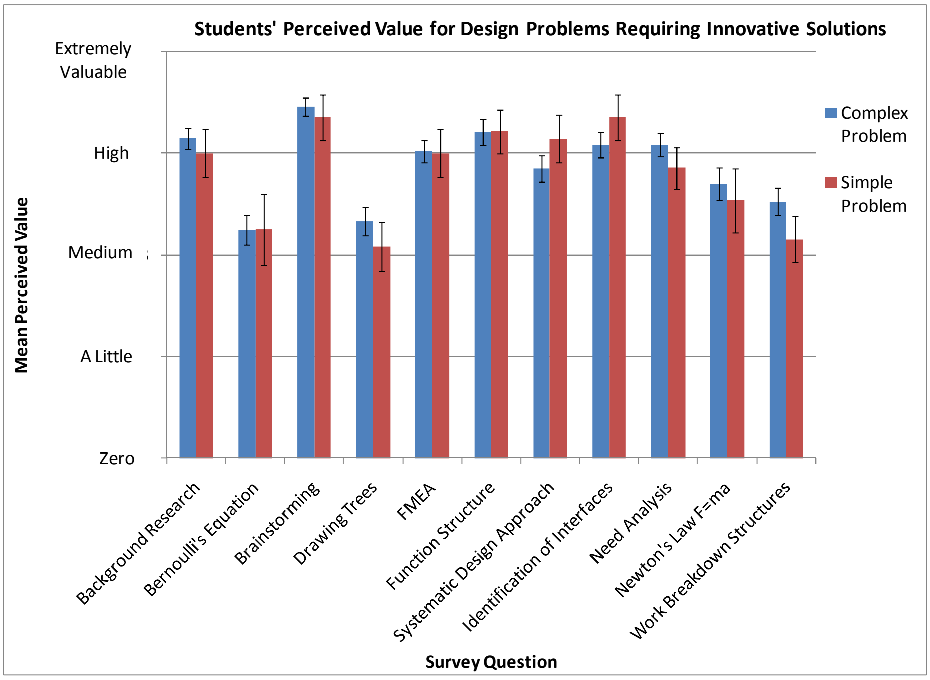


Figure 8: In general, across the different design methods, students' opinions for a method's effectiveness for problem requiring innovative solutions did not show any general trends with respect to the type of design problem they had. There are statistically signifcant trends for some of the methods (error bars are +/- one standard error).

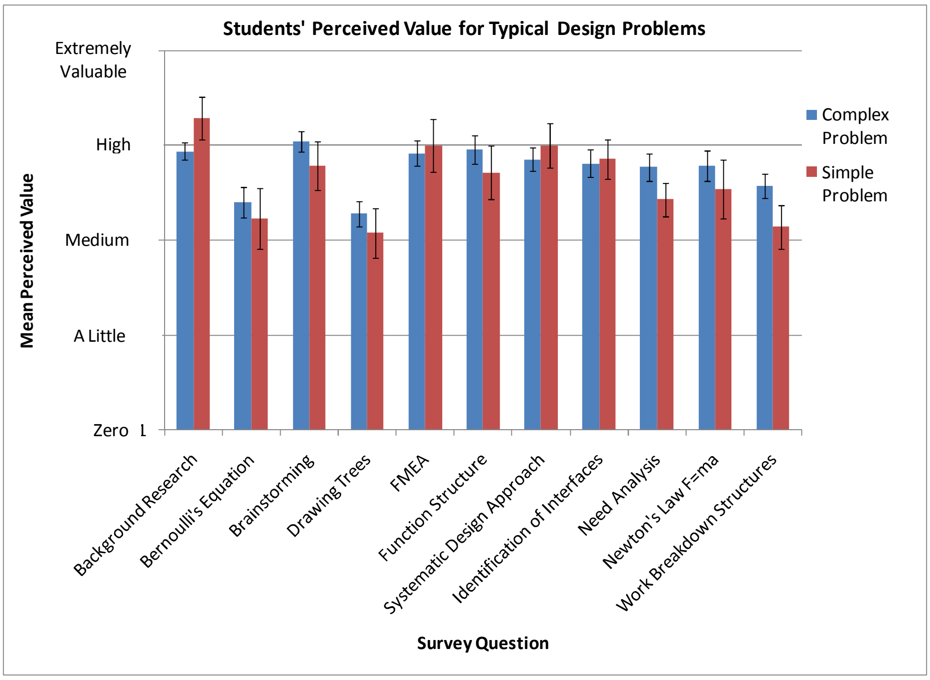


Figure 9: In general, for typical design problems, students' opinions did not vary depending on the type of design problem they had. There are statistically signifcant trends for some of the methods (error bars are +/- one standard error).

V. ADDRESSING THE HYPOTHESES AND RECOMMENDATIONS

Functional Modeling Skill Hypothesis: The interaction of the complexity of the design problem and the students' perceived future use does significantly affect their functional modeling skill. A larger sample of students in the Simple Condition is required to further confirm this results since the current sample size is limited. This study cannot determine if there is a causal relationship between the students' opinions and their attainment of functional modeling skill. It is possible that if students' do not perceive functional modeling to be a valuable skill then they also tend to put less effort into learning it.

Student Perceptions of Functional Modeling Hypothesis: There is some indication that students who work on more complex design problems will be more likely to expect to use the method in the future and this was statistically significant. There was no evidence that students with the more complex design problem valued it more.

Design Method Perception Hypothesis: In general, students who work on more complex design problems do not place greater value on the methods nor are they any more likely to use them in the future. Some of the methods show trends of greater perceived value and students expecting to use them in the future more often but these are not statistically significant with the current sample size. Future work will continue to investigate this issue.

Recommendations: When the goal is to teach students the design methods, for example in a first design methods & theory course, more complex design problems should be used. More complex design problems clearly demonstrate the effectiveness of design methods.

VI. CONCLUSIONS & FUTURE WORK

Effectively teaching students to design and apply their technical knowledge to solve real-world problems is critical. There is no clear consensus and little empirical data on what factors influence student learning and perceptions in design courses. This paper explores one factor that likely influences student learning and student perceptions of systematic design methods, the complexity of the design problem. Through a controlled comparison, this paper evaluates the effects of design problem complexity on student learning of functional modeling and their perceptions of various design methods.

The complexity of the design problem does affect student perceptions and their functional modeling ability. More complex design problems result in more positive student perceptions. Results indicate there is an interaction between student opinions and the complexity of the design problem that affects their functional modeling ability. This effect needs to be further explored with a larger sample size since in the current experiment the Simple Condition contained only 14 students. In addition, further improvements to the functional modeling measure are needed.

There are numerous other desired learning outcomes such as the ability to troubleshoot problems and make accurate assumptions that are not measured by the current study. This study evaluates a single design skill but many other skills are also critical to the design process. Future work will also focus on these other skills and other issues associated with implementation of capstone design.

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