Board 18: The Impact of Functional Modeling in an Engineering Design Curriculum

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The Impact of Functional Modeling in an Engineering Design Curriculum

Abstract
The National Science Foundation's (NSF) Division of Undergraduate Education (DUE) funded "Collaborative Research: Evaluating the Impact of Teaching Function in an Engineering Design Curriculum." The original goals of the proposal were to investigate the relationships between student knowledge level of functional modeling and 1.) the ability to explore the solution space during design, 2.) the ability to generate quality designs, and 3.) the ability represent and understand engineered systems. While the funded project work formally began in 2015, the PIs conducted initial studies on teaching functional modeling as early as 2011 [1], and in that work stated one of the research goals was to "… determine the value that functional modeling brings to the design process." This paper, and the accompanying poster aim to not only summarize and report on work done during the NSF funding period, but to also provide the relative background and context of the work and to foreshadow future design modeling research efforts.

1 Introduction and Motivation

Two of the PIs became interested in the value of teaching functional modeling when they were Graduate Teaching Assistants who had been tasked with conveying this abstract form of modeling to freshman engineering students in the mid-2000s. Most people whom have tried to teach functional modelling might agree that students do not always readily adapt to the paradigm or see the potential value added to the design process. As graduate students with a focus on design methodologies, the question began to percolate: "Is the hassle of teaching functional modeling worth it?" The work evolved from those initial questions and ultimately encompassed six unique areas around engineering design modeling: 1.) teaching method surveying, 2.) proposal of teaching methods, 3.) proposal of evaluation methods, 4.) refinement of evaluation methods, 5.) impact assessment, and 6.) exploration of mental models. A summary of research efforts thus far and their related theme(s) is summarized in Table 1.

Table 1 – Overview of Functional Modeling Research Efforts [1-13]

Teaching Method Survey	Proposed Teaching Method	Proposed Evaluation Method	Evaluation Method Refinement	Assessing Impact	Mental Model Exploration	Paper Title
X						2011 - On Teaching Functionality and Functional Modeling in an Engineering Curriculum
X	X					2012 - An Algorithmic Approach to Teaching Functionality
	X					2013 - An Investigation into the Effectiveness of an Algorithmic Approach to Teaching Functional Modeling
	X	X				2014 - A Study on Teaching Functional Modeling in a Sophomore Engineering Design Course
	X	X				2015 - Improving Students' Functional Modeling Skills: A Modeling Approach and a Scoring Rubric
		X	X			2016 - Knowledge Retention and Scoring Metrics for Functional Modeling in an Engineering Design Context
				X		2016 - Evaluating the Impact of Teaching Function in an Engineering Design Curriculum
				X		2017 - Towards Assessing Student Gains in Systems Thinking during Engineering Design
				X	X	2017 - A Bridge to Systems Thinking in Engineering Design: An Examination of Students' Ability to Identify Functions at Varying Levels of Abstraction
			X			2018 - Question-by-Question Interrater Analysis and Suggestions for Improvements of a Functional Model Scoring Rubric
		X		X	X	2018 - A Function-Based Scoring Method for Evaluating Student Mental Models of Systems
			X			2019 - An Update to a Functional Modeling Scoring Rubric with Overall and Question-Level Inter-Rater Reliability
		X		X		2019 - The Impact of Industry Experience on Engineering Graduate Students' Functional Design Modeling

In the 2011 paper surveying functional modeling teaching methods [1] two sub questions were identified to help determine the value functional modeling brings to the design process: 1.) How do you quantitatively assess the quality of any given functional model? and 2.) How do you structure a set of experiments to determine the effectiveness of modeling techniques at varying course levels? Those sub-questions lead to the hybrid functional model teaching method [2, 3] and an initial rubric that assessed the mechanics of a given functional model [5]. Initial results indicated success using the hybrid scaffolding approach to teaching function [3, 4] when compared to a basic step-by-step guide. The initial scoring rubric was successful with relatively high inter-rater reliability [4, 5], but also allowed for some interpretation discrepancies [6]. After initial studies using the scaffold approach to teaching and the binary rubric for functional model assessment, additional work sought to assess the impact of teaching function [8, 9] as well as rubric refinement [10, 12]. Results thus far have indicated that teaching function provides students a mechanism to decompose engineered systems [9, 13], and preliminary data suggests the recognition of function improves students' mental models [11]. Follow on work will continue to explore the link between functional modeling skills and the ability to generate accurate mental models.

2 Background

A function model is a visual representation of the functions of a given product used for a certain purpose [14]. An example functional model of a hair dryer is shown in Figure 1, where functions operate on incoming/outgoing material, energy, and signal flows. Functional modeling works to identify unique design opportunities by reducing design fixation, therefore leading to more innovation during the ideation phase. The PI's primary hypothesis throughout their research is that teaching functional modeling to engineering students will improve their design quality while increasing their understanding of systems as a whole.

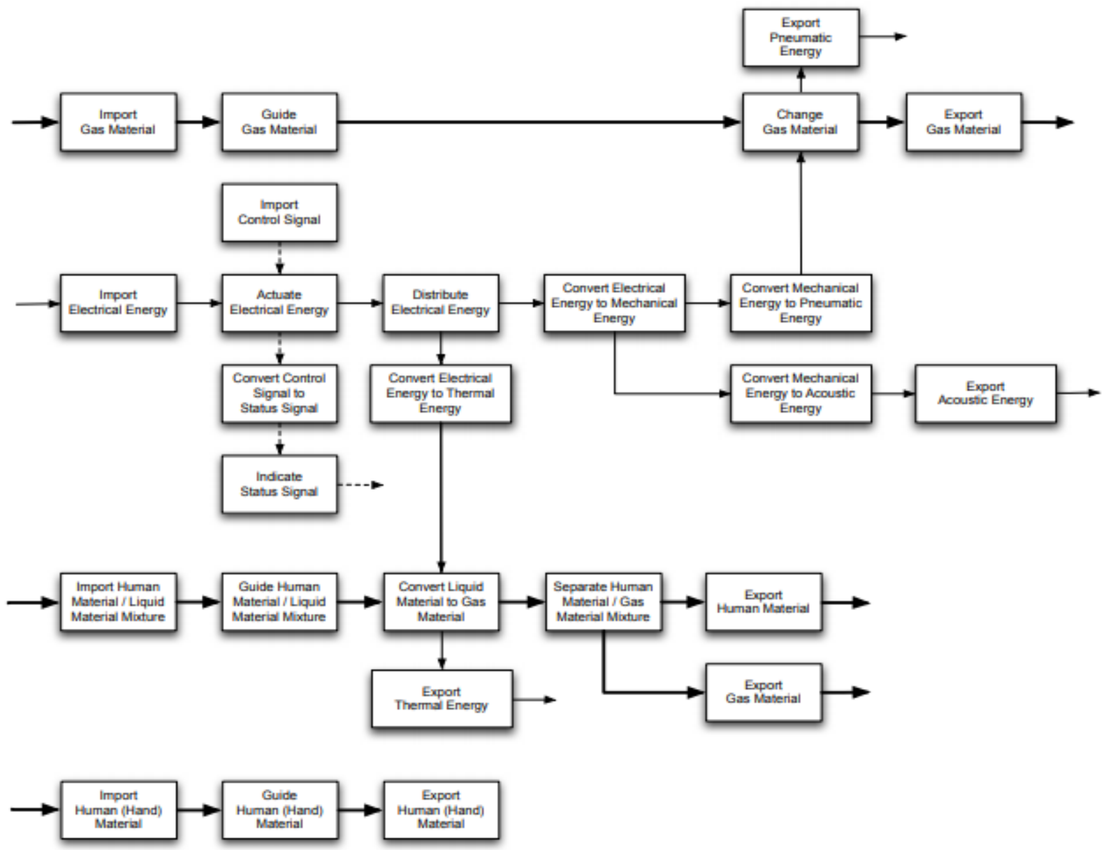

Figure 1. Example Functional Model of a Hair Dryer

Initial work done by the PIs showed that students who were only taught functional modeling through lecture were outperformed by students who were given additional help outside of lecture using a step-by-step example and rules for model generation. To further investigate the impact of different functional model teaching tools on students' understanding, the PIs studied a control group who only learned the basic meaning of function and a treatment group who received functional modeling instruction. Student assessment was comprised of a FunSkill quiz which tested the students' ability to identify function, describe functionality, understand functional translation of design objectives, and create a functional model. The follow-on study showed that the treatment group successfully outperformed the control group in differentiating different design's function, enumerating functions, and generating higher quality functional models.

Further studies uncovered that students appear to be able to retain their ability to generate adequate functional models even after seven weeks of not practicing functional modeling generation. In a continuation of the exploration of quantifying functional modeling's impact on the design process, it was found that students who learned about functional modeling and functional enumeration appeared to be better at identifying low-level functions that are critical for systems thinking compared to the students who were taught only functional enumeration.

Stemming from the initial function-based investigations, the PIs have become interested students' mental models of engineering systems, eliciting them, and seeking to leverage functional modeling as a tool to help students develop mental models and system understanding. Most recently, the team developed a tool to assess mental models and examine the impact of functional modeling on that mental model. Initial studies have asked students to break down a product into its components. They were then taught functionality and were asked to repeat the first task. Initial results show that students appeared to be unable to distinguish functional similarities of two products that were unfamiliar to them. However, the same students were able to distinguish functional similarities of products they were familiar with prior to the study.

3 Studies and Findings

In their introductory study in 2015, the researchers completed a study to determine the most effective method of teaching students how to generate functional models [5]. This paper was also used to showcase the functional modeling scoring rubric that the researchers developed in order to test the quality of student's functional models. The results from the scoring rubric showed that the students who were only taught functional models were outperformed by the students who were taught functional models, shown a functional modeling example, and given the grammar rules for functional modeling. However, there was no statistical difference between the group of students who received both the functional modeling lesson and example and the group of students who were also given the grammar rules. From the results, the PIs determined that more effort must be placed into understanding how students learn functional modeling and how their functional modeling abilities change over time.

To qualitatively analyze the effectiveness of teaching functional modeling in an engineering classroom over time, a longitudinal study was performed where students who were taught functional modeling were compared to students who were only taught the basic meaning of function [7]. This study was completed throughout select students' sophomore, junior, and senior years. To investigate the significance of function modeling training technique, two control groups of students, sections C and D, were just taught the basic meaning of function, while two treatment groups of students, sections A and B, received function modeling instructions. To assess the student's comprehension of the functional model, a four-question quiz, known as FunSkill, was administered to both groups of students. Specifically, the quiz tested students' ability to identify function, describe functionality, understand functional translation of design objectives, and create a functional model. The first three questions were evaluated by engineering professors, while question 4 was evaluated by two trained graduate students. For the first question, there was no significant different between the control and treatment group which indicates that both groups of students were equally able to identify the differences between functional statements and design attributes. This was expected by the PIs since both groups were taught the meaning of function. For questions 2 and 3, the scoring required three parts: general correction, high-level function (i.e. black box), and low-level function (i.e. component-level). Based on the results from questions 2 and 3, the hypothesis that students who are taught functional will outperform students who were only taught the definition of function could neither be supported nor repudiated. However, question 4 which evaluated functional models created by the students did support the claim that the treatment group would outperform the control group in differentiating different design's function, enumerating functions, and generating higher quality functional models. The control group was unable to generate black box models and sub-functional functional models though this could have been due to rather time constraint means. In addition, this study proved that FunSkill quiz can be used as to measure the function modeling skill of students.

In order to understand how functional modeling abilities change over time, the PIs conducted a study over a 8 week period to see how student's functional models developed [6]. The students in this study completed both a functional modeling homework assignment (FunHWRK) toward the beginning of the semester and a FunSkill test toward the end of the semester. By running two different types of assignment with the same goal at different times, the researchers were able to not only analyze if students can retain their functional modeling ability overtime, but also the researchers were able to see differences between how students preformed on the homework assignment versus and in-class, low-stakes test. The results showed that students are able to maintain their functional modeling capability over a seven-week period. The students also performed better on their homework than on the quiz which is understandable as they had a week to complete the homework and fifteen minutes to complete the quiz. However, while completing this study, the researchers found that parts of their functional modeling rubric were ambiguous and needed better clarification to improve the inter-rater reliability.

Another study completed by the PIs compared students who were taught functional modeling and functional enumeration with students who were only taught functional enumeration [9]. The goal of this comparison was to determine if the different teaching material impacted the students' ability to recognize high level and low level functions. The researchers understand that this recognitional ability is crucial for systems thinking and therefore is important to the engineering community. In order to test the difference between the two groups, the PIs hypothesized that the functional modeling and functional enumeration group will provide more low level functions and interface functions than the functional enumeration group showing that they think about the system as a whole rather than focusing on specific components. The results of the study supported the PIs hypothesis showing that the students who were taught both functional modeling and enumeration were better at viewing a system holistically than the functional enumeration students.

In an additional study, the Systems Assessment Test (SysTest) was utilized as a calibration for measuring thinking to further compare the previous two groups [8]. The format of the test was Yes/No, and the responses were analyzed by the PIs. This test was used to see if the students who were taught both functional modeling and functional enumeration used their systems thinking abilities more than the functional enumeration group during engineering design tasks. The results showed that the students who were taught function modeling and functional enumeration were able to view the system more abstractly and apply more modeling techniques. However, the students who were only taught functional enumeration were able to produce more functions which may possibly be a quantity versus quality issue.

In an effort to develop an instrument that can measure the mental model of an engineering student, the PIs tasked students with drawing a car radiator and hair dryer in terms of their basic components [15]. The students were then taught functional modeling and were asked the draw the devices' components again. Based on the results of the study, the students were not successive at identifying the functionality of more complex engineering systems (car radiator) despite being able to successively identify simpler systems (hair dryer) which have the same basic functionality. The results seem to indicate that students have a more developed mental model for familiar products then for unfamiliar products.

Further study of students' mental models was done by the PIs in 2018 [11]. Students were given two systems, a hair dryer and car radiator. Then, the students, given the required functionality for each product, were required to fill in and label the components that would help each product achieve said functionality. The students were then taught functionality and were asked to repeat the previous task. This testing was used to identify similar functional modules and students' recognition ability. The results were tested using a rubric developed with a functional Module Heuristic-based approach. Based on the results, it appears that students' mental models do not significantly change after being taught functional modeling.

The previously discussed rubric ambiguity [6] was addressed by the PIs in 2018 [10] by calculating the interrater agreement at the question level and making suggestions for improvement. One such solution to the issue of ambiguity was quantifying the parameters of the rubric such as stating "at least 80%" instead of "overwhelming majority". In addition, the rubric was evolved to classify the functions into specific categories of low-level, interface, and high-level functions.

4 Summary and Future Work

The work done by the PIs thus far has been beneficial to the engineering community. Functional modeling is taught in many engineering curriculums [16], however, there is yet to be another published rubrics for scoring functional models as was created by the PIs. Because of the importance of a scoring method for functional models, much time and effort has been placed into improving the rubric in order to make the rubric accessible to people of any level of engineering expertise. Furthermore, the PIs work has helped pave the way to understanding how functional modeling impacts students' mental models as well as how to best teach functional modeling to engineering students.

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