A longitudinal exploration of students' functional modeling abilities

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A Longitudinal Exploration of Students' Functional Modeling Abilities

Abstract
Teaching function is often regarded as an important practice to foster systems thinking skills in engineering students. The specifics of how function encourages systems thinking habits and improves design abilities, however, are not well understood. An instrument and accompanying scoring rubrics referred to as 'Funskill' have been developed and validated throughout previous research in an effort to gauge students understanding of, and ability to apply functional thinking. In this research, longitudinal data was collected from eight undergraduate engineering students' sophomore, junior, and senior year, and data were analyzed in order to observe how engineering students' functional aptitude has progressed throughout a design-oriented undergraduate engineering curriculum with multiple points of exposure to functional thinking. Results show that students' competency with function does not improve as they progress throughout their undergraduate career. That being said students did demonstrate some degree of systems thinking in this study, but the growth of those skills over time remains ambiguous as FunSkill and its' corresponding scoring instruments were not explicitly generated to capture students' systems aptitude. Results from FunSkill are discussed and observations regarding the development of students' design competency as well as the success and limitations of Funskill are deliberated. This work is part of ongoing research that explores how various instructional tools impact engineering students' systems thinking tendencies and design skills.

1. Introduction

As the complexity of the infrastructure, consumer electronics, and virtually all other engineered systems increases, so too, does the need for engineering programs to graduate engineers and designers capable of tackling the complex design problems associated with these increasingly intricate systems. Effective design is something that novice engineers and engineering students have routinely struggled with in the absence of explicit education or extensive industry experience [1]. This is largely attributed to the evolutionarily dictated propensity for humans to tackle immediate surface-level problems, as opposed to pursuing an organized and comprehensive design process [2]. Applying techniques such as functional modeling during engineering design pushes engineering designers to think about systems hierarchically, but also, abstractly-*hopefully moving one's focus beyond surface-level concerns*. Accordingly, we consider this successful application of function in engineering design to be systems thinking—a skillset often attributed broadly to the field of systems engineering—but one that is also noted across many disciplines and broadly concerns one's ability to think in systems, i.e., having a systems mindset.

This work is part of a larger effort that explores the effect of functional modeling on students' design abilities and the development of systems thinking skills. This research is conducted to better understand what skills constitute good designers, and how those skills can be developed and taught in order to better prepare students throughout engineering curriculums to enter a complex and messy world. Results are presented from a longitudinal research study investigating how engineering students in a design-oriented, engineering curriculum abstract systems through function and how this ability to abstract systems through function changes as the student progresses through their undergraduate engineering career. This paper builds off previous research exploring how functional modeling correlates with the development of students' systems thinking ability [3, 4].

2. Background

First, it is important to provide a definition of what is meant when referring to a "system". The late Donnella Meadows, in her well-regarded text, *Thinking in Systems* [5], defines a system as follows:

> *A system isn't just any old collection of things. A system is an interconnected set of elements that is coherently organized in a way that achieves something … A system must consist of three kinds of things: elements, interconnections, and a function or purpose.*
>
> *Donella H. Meadows, p11*

From this definition specifically, in conjunction with Meadows's recognition of the need for a system to include the constituents, interconnected elements, and have a purpose, we can also deduce that a system has order. Successful systems thinkers emphasize the connections between sub-systems and parts of a greater system and favor a holistic view of systems as opposed to designing it about one given component or set of components [1]. The attributes and characteristics that define systems thinkers, however, have been proven difficult to instill in both engineering students as well as less experienced engineers in industry, often only being recognized amongst only the experienced and senior engineers [2].

Systems thinking skills, though, are not necessarily an exclusive function of engineering experience in the workplace, but something that can be fostered through explicit instruction. One discipline of engineering, systems engineering, is in fact largely concerned with designing of systems such that components and subsystems of a greater mechanism have synergy so that they can more effectively achieve that systems' overall functionality [6]. INCOSE, the professional society for Systems Engineering, defines systems engineering as the "transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods" [7].

This pursuit of systems thinking is relevant for all design work and within all disciplines of engineering given its' value for designing complex systems [1]. Accordingly, what qualities define successful systems engineers as well as how to instill these qualities in engineering students has been a major area of research amongst engineering educators. In a study conducted amongst engineering professionals, most of whom were systems engineers, researchers found that those exposed to formal education in systems thinking as well as had experience with academic projects in controlled environments displayed a propensity for systems thinking and aptitude in systems design [8]. Research efforts to investigate systems thinking competencies amongst undergraduate engineering students have shown that students generally do not exhibit a strong capacity for systems thinking, highlighting the need for added or reformed education on systems thinking in engineering curriculum [9].

One major area of focus for researchers and engineering educators to help enhance students' capacity and propensity for systems thinking has been system abstraction. In analyzing and designing complex systems students and novice designers often encounter and get stuck on components and sub-systems they do not understand and are overwhelmed by the complexity and complicated organizational structures of the systems they encounter [9, 10]. System abstractions reduce these intricate and vast systems into simplified models that are more manageable without misrepresenting the system and its functionality [8, 11]. One form of system abstraction is functional modeling [12]. Functional modeling abstracts a system so that it is free from the specific means and components it's comprised of, reducing it to what it is that system must do [13].

2.1 Functional Modeling

Function, a concept stemming broadly from the field of Value Analysis [14], has been identified by literature as playing an important role in systems approaches to design, largely by providing an effective framework for communicating systems [11], and more specifically, to discuss a system through function allows for low-level functionality to be discussed in the context of overall system functionality [3, 11]. The consideration of low-level functions with system-level functions necessitates emphasis on connections and relationships desired purpose and context [12]. Here, we see a link to the definition of a system provided by Meadows, which again denotes the requirement of order, constituents, interconnected elements, and a purpose. Functional models provide each of these requirements through an abstraction of related transformations to flows (energies, materials, and information) where flows create the interconnections, transformations represent the constituents, modeling ontologies such as the Functional Basis [15] provide order, and where design objectives provide purpose [16].

Functional models can be generated at various levels of detail for various applications, from black box models that represent overall system functionality to highly detailed functional models that entail the function of every component and feature of a system [12]. Functional models consist of a series of functions strung together in interrelated chains of flows, and flows provide direct linkages hierarchically through levels of model abstraction [16]. Chains of functions operate on and conserve the flows of energy, material, and information that enter and leave the user-prescribed system boundary [17]. Functional modeling is widely believed to promote the assumption of a holistic systems [3, 18] as well as reduces idea fixation as well as promote "enhanced creativity, clearer understanding of the design goals, and simpler decoupling of sub-problems" [19]. Interestingly, though, functional modeling as presented in engineering design texts does not appear to have a formally established connection to systems thinking.

In previous work investigating the less established connection between functional modelling and systems thinking, discrepancies in the level of functional abstraction in undergraduate engineering students was noted [18]. While many students described system-level functionality (functions that represent the system as a whole), many students simultaneously enumerated low-level functions (those functions that represent transformations of flows critical to operation of the system, but not describing the entire system, such as *guide mechanical energy*) [3]. These two levels of abstracted functions when juxtaposed indicate that students are viewing the system holistically, and they are making connections that represent systems thinking [12]. This suggests that functional modeling has the ability to help foster the systems thinking skills in undergraduate engineering students providing the basis for research on the connection between functional modeling and systems thinking. The research presented in this paper explores that connection through a longitudinal study on how students' understanding of function changes over time.

2.2 Teaching and Assessing Function

In a review of engineering design texts describing functional modeling, Nagel and Bohm identified seven approaches which broadly lead to two types of models: flow-based models and hierarchical tree-based models [17]. Additionally, they proposed their own algorithmic approach [13] and developed a rubric for assessing functional models based on functional modeling conventions for flow-based models [20, 21]—the approach their assessment of teaching approaches indicated to be most prevalent in design texts. Toward understanding students' abilities to not only generate functional models, but also, to understand the concept of function, Linsey et al. developed the skills test: FunSkill [22].

FunSkill is a tool used for the assessment of students' ability to identify and generate functions as well as how accurately and completely students develop a more formal functional model of a provided system [22]. While largely concerned with capturing students' ability to retain knowledge concerning function, FunSkill has proven to be capable of casting a light on how students view systems, as well as whether they are exercising systems thinking skills during their functional model generation [3]. Funskill provides this insight by allowing the quality and completeness of connections in students system representations to be evaluated, as well as providing the opportunity to investigate the level of abstraction at which students identify functions and model systems. Previous research using the FunSkill instrument demonstrated some interesting systems thinking characteristics: an ability to recognize systems boundaries as well as the flows across the systems boundaries and generation of low-level and interface functions while also not ignoring high-level system functionality [3]. Overall, while the FunSkill exercise was explicitly generated to benchmark students' competency with enumerating functions and developing functional models, it has additional value in speaking towards students' systems thinking abilities as well.

The demonstrated applicability of FunSkill to assess students' functional modeling ability as well as its' applicability toward identifying characteristics of systems thinkers (e.g., thinking about systems at varying levels of abstraction, understanding systems boundaries, and recognizing order and purpose) led the research team to adopt the instrument for the longitudinal study presented in this paper. A rubric similar to the one developed by Tomko et al. in [3] is also employed in this study with some additions, which are discussed in detail in the following section.

3. Methodology

This three-year longitudinal study began during students' sophomore year at a regional university in the south. Students were all enrolled in an engineering design, systems, and sustainability focused engineering program and were working toward the completion of a non-discipline specific bachelor of science degree in engineering. All students were recruited into this Institutional Review Board approved study during their sophomore year while enrolled in the first of six engineering design process courses in the program. Recruitment occurred following instruction in functional modeling in the seventh week of the semester. Seventy-nine students voluntarily consented to be a part of this study during this initial recruitment and completed the FunSkill instrument during regular class meeting times.

Course instruction on function consisted of three parts: contextualization, function as an abstraction, and function as a modeling tool. During contextualization, the concept of function was introduced and placed within the context of other conceptual design concepts already taught: design space, specifications, constraints, functions, and design objectives. Figure 1 was used during class to help describe how understanding of these concepts allows for further clarification of the overall design problem. Discussion of function as a system abstraction tool focuses on the notion of function as a solution independent representation of systems, sub-systems, and components where students work through examples and identify appropriate functions. Toward learning functional modeling, students developed functional models of an automated soap dispenser and a lawn mower during class following detailed discussion of the functional model of an iPod. During the functional modeling instruction, students were provided with the Functional Modeling Grammar Rules [13, 21] to guide their process, and its use was demonstrated during class. For homework, all students were asked to generate a functional model of a bicycle independently, and following feedback on their individual models, students applied functional modeling to their course project, which for this cohort, was to design and build a human-powered vehicle for an individual with cerebral palsy.

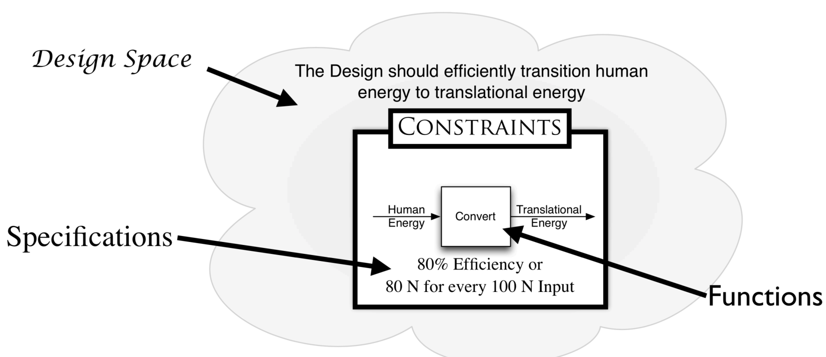

Figure 1: *Image provided to students during lecture on function and functional model used to contextualize function within previously taught design concepts.*

Student participants completed the FunSkill instrument two weeks following course instruction after individual practice on functional modeling completed as homework and receipt of instructor-provided feedback on individually generated functional models. Completion occurred at the end of class time such that students who opted not to participate could leave. Students were given as much time as needed to complete the FunSkill instrument, but in practice, students likely took approximately 20 minutes to complete the instrument.

The remaining two data collections occurred when this cohort of students were juniors and were seniors with both data collections occurring during the spring semester outside of class time in the evening at approximately 5:30PM. Students were recruited to participate via an announcement sent using the university's course management system. Student participants were compensated via gift cards of $20 for their time completing the FunSkill instrument, and all students were given unlimited amount of time to complete the FunSkill instrument. As juniors, 16 students elected to participate in the study and completed the FunSkill instrument; as seniors, 14 students elected to participate and completed FunSkill. Across all three data collections, there was an overlap of 8 students representing approximately 11% of the total graduating senior class at the university where this data was collected. Given students volunteered to participate outside of class time for the longitudinal portion of this study, they may have represented a more motivated sample size when compared to the entire 79-person pool that initially completed FunSkill. This in part proved valuable as students committed themselves to completing FunSkill in its entirety, but may also make for skewed results that are not necessarily indicative of the entire population of students in the engineering program within which this research was conducted. Also, as student participants were compensated with gift cards during their junior and senior year, internal motivation during those two years may not be the only factor compelling students to participate in this research.

The FunSkill instrument was identical at all three points of data collection, and as a result participants may have experienced some learning effects while completing the survey for the second and third time. That being said, there is no set of correct answers and most questions are open ended, so such learning effects should be minimal. Furthermore, students did not receive feedback on their performance between data collections and as a result did not know with certainty the "correctness" of their answers.

3.1 Assessment Instrument

The FunSkill instrument is comprised of four questions [22]:

1. Question one prompts to rate statements such as, *weighs less than 200 lbs*, and *convert human energy to rotational energy*, as either a not a function (the first statement) or a function (the second statement). The question is provided as a table.
2. Question two prompts to *list four functions of the fingernail clipper* and a fingernail clipper is pictured. Four blanks are provided allowing the examinee to write any statement desired.
3. Question three prompts to *name four of the functions to meet the listed design objectives for a portable device to be used in a dorm room … to allow you to wash your hands and your dishes* and four design objectives follow. Again, four blanks are provided allowing the examinee to write any statement desired.
4. Question four prompts for the creation of a black box model and a functional model of a bicycle. Three design objectives are provided: *The bicycle will be easy to peddle, …will indicate velocity,* and *…will easily go fast.* A picture of bicycle is provided, and the remainder of the page is blank to allow for free expression by the examinee.

3.2 Hypothesis

Three hypotheses found this study:

1. Students ability to identify function from other design constructs as measured by Question 1would decrease each year following initial instruction during sophomore year.
2. Students systems thinking ability as measured by Question 2 and 3 would increase each year following initial instruction, where systems thinking ability would be demonstrated through:
    a. Noting high-level functions,

b. Noting low-level functions,
c. Noting system boundaries, and
d. Noting system inputs and outputs.

3. Students functional modeling ability as measured by Question 4 would decrease each year following initial instruction during sophomore year.

		Question	Description	Grade Scale	Case	Synonymous Verbs
Correct	1	# Correct Functions	The number of functions that are relevant, originial, and adhere to functional grammar rules. See table for repetitive functions.	Count	1	Wash/Clean/Rinse/Sanitize
	2	High Level	Functions related to high level systems thinking principles, namely conservation of energy and mass, and represent critical system functions.	Count	2	Store/Contain/Hold
	3	Low Level	Functions related to the secondary and tertiary functionality of a system or functions that allow the system as a whole to operate.	Count	3	Remove/Export/Separate
	4	Signal	Functions related to the user interface or operation of a system.	Count	4	Import/Supply/Provide
Incorrect	5	# Incorrect Functions	The number of functions that are irrelevant, repetitive, or do not adhere to functional grammar rules.	Count		
	6	Repetitive	One function is listed multiple times, See table for repetitive functions.	Count		
	7	Incoherent	Function enumerated is irrelevant or nonsensical	Count		
	8	Not Verb/Noun Pair	Function enumerated is not in the form of a verb/noun pair	Count		
	9	Other	Number of functions wrong for other reasons. If so describe briefly	Count		
System Boundary	9	System Boundary	Number of functions where an EMS flow crosses a System boundary	Count		
	9a	EMS Recognized	Water	1/0		
	9b		Soap	1/0		
	9c		Plates	1/0		
	9d		Dirt,Grime, etc	1/0		
	9e		Operator Material	1/0		
	9f		Operator Signal	1/0		
	10	Inputs Recognized?	Are some or all inputs recognized	1/0.5/0		
	11	Outputs Recognized	Are some or all outputs recognized	1/0.5/0		
	12	Human Input	Is the operator regarded as inside the system boundary?	1/0		

Figure 2: *Rubric for assessing function-flow responses used to assess Questions 2 and 3 on the FunSkill instrument.*

3.3 Scoring

To score the FunSkill instrument, three strategies were employed. For Question 1, responses were scored simply as correct or incorrect as to whether the students correctly identified the response as a function or not. Question 1 was scored only by one rater, an undergraduate student at the university where this study occurred. Correct and incorrect responses were identified prior to scoring by the entire research team.

For Questions 2 and 3, while an existing strategy for assessing systems thinking ability had been identified [3], the team recognized that this previous scoring method lacked the resolution necessary to capture different types of energy-material-information flows across the system boundary or recognize the generation of a system boundary—both response features of interest based on the hypotheses. Accordingly, a new 12-question rubric was developed in an effort to capture a potential change in this phenomenon as students progressed from sophomore to senior year. This final rubric was based on the Murphy et al. rubric for assessing functional models [20] and is provided as in Figure 2.

This 12-question rubric scores FunSkill Question 2 and 3 not only based on whether or not responses are correct and appropriate as previous scoring approaches have, but also, categorizes responses based on what type of function is being assessed, for what reason the function response is incorrect, if appropriate, and whether or not the function being assessed is related to the system boundary. Functions related to a system boundary are further categorized based on what specific energy-material-information flow was enumerated, whether the function represented an input or output into the system, as well as whether or not participants recognized an operator's interaction with the system. Correct functions are categorized into either High-Level, Low-Level, or Signal related functions. High-level functions concern major system functionality, or the conservation of energy or material. Low-level functions represent a more specific functionality the system must produce. Information functions are related to user interface and those that control the system behavior. Incorrect functions are sorted into categories that indicate why they are wrong as follows: repetitive, incoherent, fail to follow grammar rules, or other. Functions related to the system boundary are counted, and the type of EMS flow they constitute, whether it is an input or output, or is related to the operator is indicated as well.

To ensure that this 12-question FunSkill rubric was working as desired, two students, one an undergraduate student at the university where the study occurred and one a graduate student at an unaffiliated university with significant functional modeling experience, both scored all FunSkill assessments. For the 12-question scoring rubric, when scoring Questions 2 and 3, an agreement of 71.2% was identified across both questions, though the agreement was 67.2% when only looking at Questions 9 through 12 of the 12-question rubric.

For Question 4, where students were asked to draw a functional model, the functional models were scored using an existing functional modeling rubric published in the *Journal of Mechanical Design* by Murphy et al. [20]. The students also independently applied the Murphy et al. rubric when scoring Question 4. When using the Murphy et al. rubric, there was initial substantial disagreement on Questions 12, 14, 19 and 20. Following review of the 'expert examples', the scorers realized that one misunderstood several questions. Following this discussion between scorers this disagreement was rectified and an agreement of 83.3% was reached.

4. Results

The first question on FunSkill is largely concerned with identifying whether or not participants can correctly identify functions while observing the corresponding grammar rules. T-test results found $\alpha = 0.07$ between sophomore and senior engineering students. While this result is not in and of itself significant, considering the sample size of this research, it is not entirely trivial either (the sample size is eight students). This nearly significant decline in the results for the first question seems to point to seniors perhaps not retaining their nuanced knowledge of the grammar rules associated with function and functional modeling.

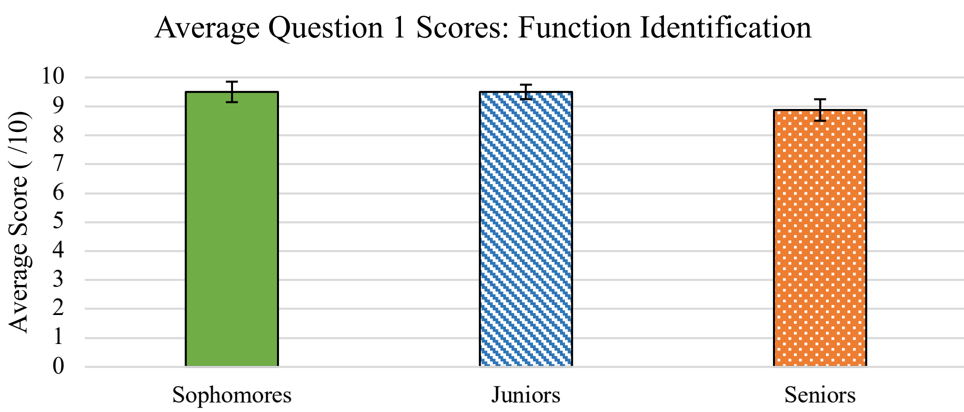

Figure 3: *Question 1 average score comparison for eight sophomore, junior, and senior students that completed the FunSkill assessment three times longitudinally.*

Results from the 12-question rubric showed little change overall from sophomore to senior year when applied to both Question 2 and Question 3. While the deterioration of students responses from Question 1 lead researchers to believe that perhaps students systems thinking skills were not stagnating as the preliminary analysis of Questions 2 and 3 would suggest, but were perhaps improving, and that improvement could not be captured by FunSkill as students could not effectively communicate the systems they encountered with function. In other words, the mechanics of specific design phrases and functional grammar rules might have presented a challenge for juniors and seniors who had not recently been exposed to these subjects, but the concept of function as a verb-noun pair representing transformations of flows remained. As a result, students may have retained their functional knowledge and successfully developed systems thinking skills, but could not aptly communicate them as this exercise depends on a solid grasp of functional grammar rules and modeling conventions. If nothing else however, the insignificant change from sophomore to senior year would indicate students are generally retaining their knowledge of function.

Figure 4 shows results from the second question of FunSkill scored exclusively by the portion of the 12-question rubric concerned with system boundaries and interface functions (Questions 9-12). Again, the results from this secondary analysis are insignificant, it is difficult still to concretely claim students' systems thinking abilities are not growing. This is largely because per the 12-question rubric, a precursor to being counted as a system boundary related is being correct, which is impossible if a given function violates the grammar rules (i.e., student responses appear to indicate thinking about system boundaries even if not correct functionally). Even still, however, a trend of improvement was noted, and while this trend is slight the fact that student's recognition of systems thinking did not deteriorate at the rate student's retention of grammar rules did is encouraging in and of itself.

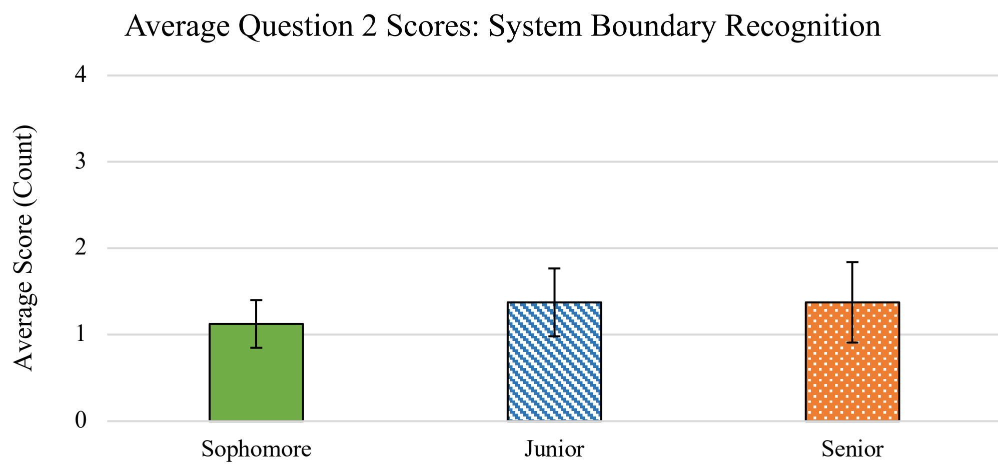

Figure 4: *Question 2 average score comparison for eight sophomore, junior, and senior students that completed the FunSkill assessment three times longitudinally.*

Additionally, it was noted that throughout Questions 2 and 3, FunSkill participants did demonstrate a preference for enumerating low-level functions, as can be seen in Figures 5 and 6.

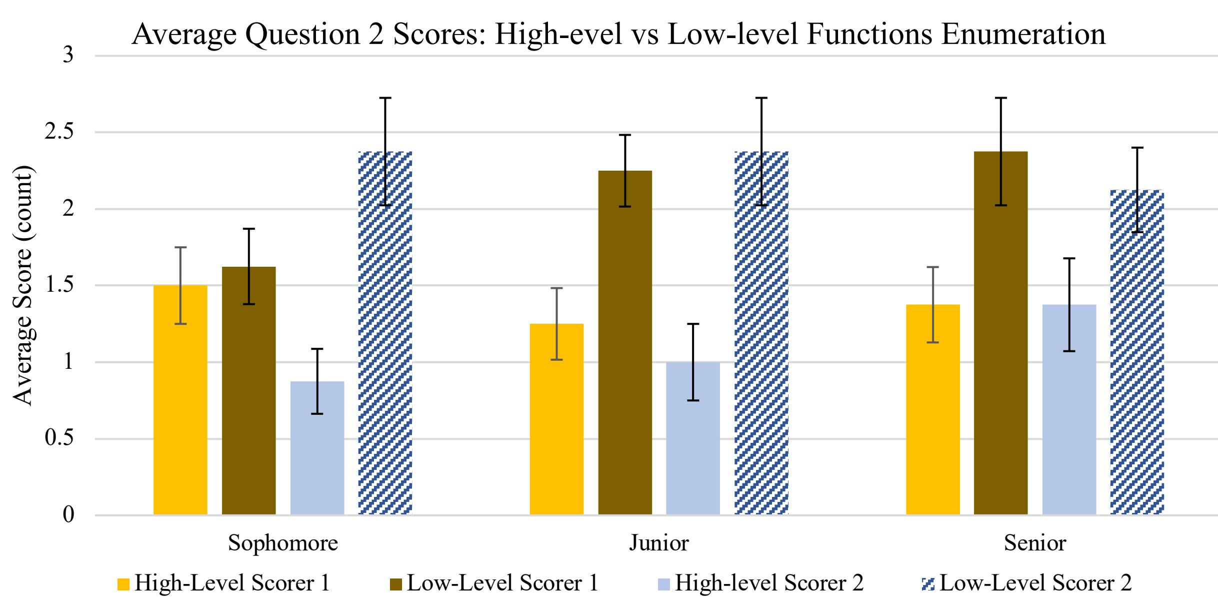

Figure 5. *Question 2 average number of high-level and low-level functions enumerated. Results from both scorers are included, and error bars represent +/- one std. error*

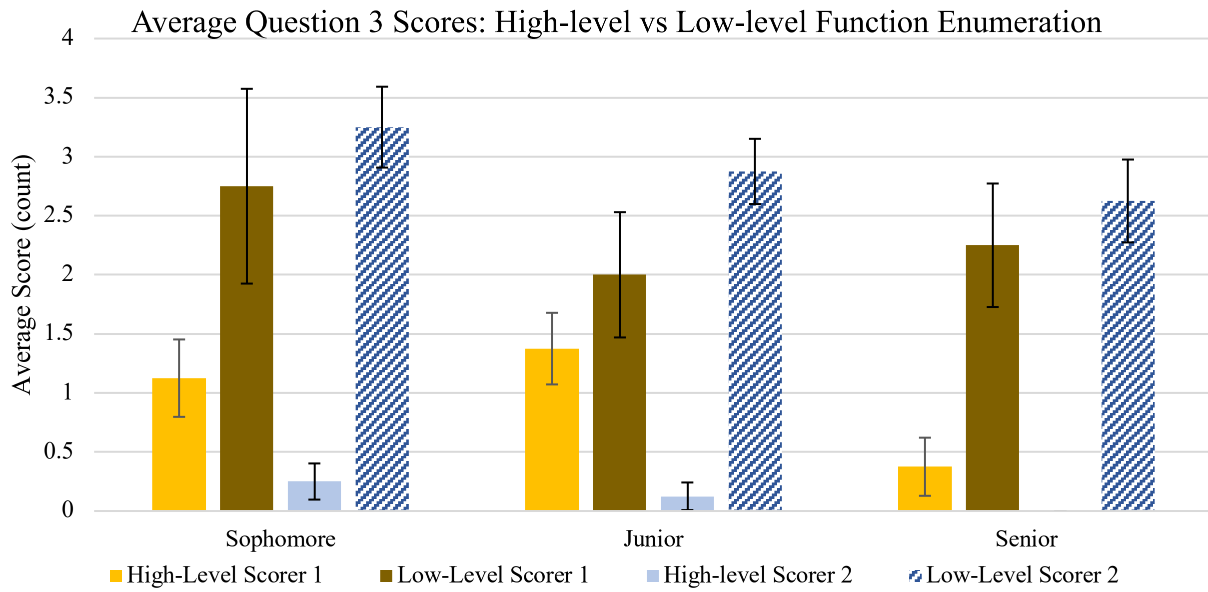

Figure 6. *Question 3 average number of high-level and low-level functions enumerated. Results from both scorers are included, and error bars represent +/- one std. error*

The analysis presented in Figure 5 and Figure 6 of high-level and low-level responses did not achieve inner-rater reliability for either Question 2 or 3 of FunSkill. This is largely attributed to the small sample size (n=8), as well as that the questions these charts are representing are count questions opposed to a simple true/false. Accordingly, results from both scorers (denoted as scorer 1 and 2) are shown, to allow for a broader discussion of trends as inner-rater reliability was not achieved. In both questions a major discrepancy was noted between the number of high-level functions enumerated compared to low-level functions. Both scorers found that for almost every academic year students were scored at, there was significance between the number of high-level and low-level functions enumerated for both questions 2 and 3. These results corroborate previous findings that students tend to enumerate both high and low-level functions in functional enumeration exercises and substantiate the claim that students are assuming a systems thinking approach to this exercise [3].

For Figure 7, there was no statistical difference between sophomore, junior, or senior engineering students in regards to the accuracy and completeness of students' functional models, indicating that working with function across their junior and senior years did not enhance their ability to abstract systems into functional models. Interestingly, students' functional models did not deteriorate in subsequent years. This lack of improvement in functional modeling performance is not entirely surprising, as these students receive a more thorough education in function during their sophomore year. As upperclassmen, students work with function in both their design and systems engineering coursework, but the students are by and large not generating full functional models, instead they developing black box models, or simply focusing on system functionality as opposed to specific means and components. While participating in such exercises did not seemingly bolster students' ability to generate functional models, returning to the topic sparingly does appear to be an effective practice to instill the skills necessary to continue to generate these nuanced models.

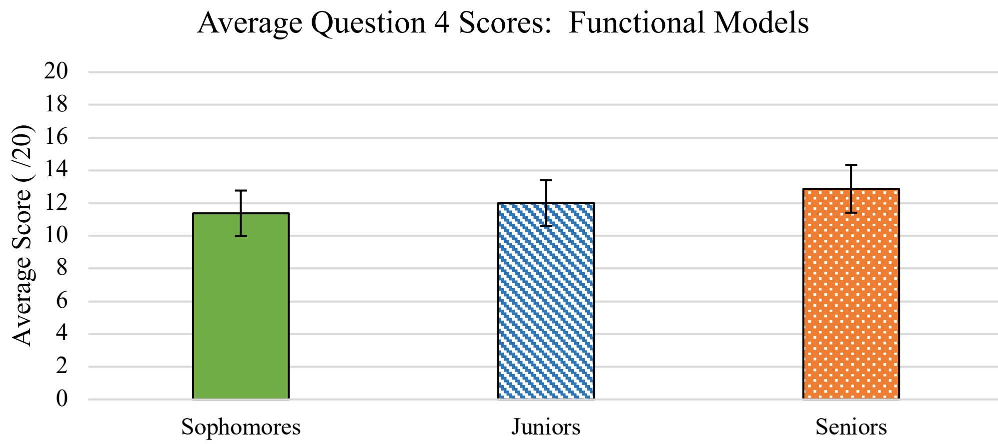

Figure 7: *Question 4 average score comparison for eight sophomore, junior, and senior students that completed the FunSkill assessment three times longitudinally.*

6. Discussion

While students' FunSkill scores did not improve as they progressed throughout their undergraduate careers, the students did retain their knowledge of function throughout this period and demonstrated that their ability to abstract systems into functional models did not deteriorate over time. Such a decline in functional modeling aptitude was expected (Hypothesis 3). Students receive a formal lecture about function and functional modelling in their sophomore year prior to any data collection and are exposed to function throughout their education. Students do not receive formal education in function after sophomore year, and as a result, we anticipated students would not completely retain this knowledge over time. Retention of the grammar rules and conventions associated with generating models in particular was expected to worsen, as it did, over the period students were tested (Hypothesis 1), as correctly applying these rules has shown not to be an intuitive process, but instead, something that must be explicitly taught [21]. Even still undergraduates' functional models did not suffer in regard to these rules and conventions as time progressed.

While functional modeling is not explicitly taught, nor is it a fundamental aspect of upper-level coursework, students do continue to work with function and similar modeling strategies throughout their undergraduate careers. Throughout their coursework students often use function to describe complex systems and sub-systems they encounter, as well as generate models similar to the black box models (as used in formal functional modeling) to both make systems more manageable, as well as allow for discussion about the input output relationship of a system and its' sub-systems. Accordingly, we postulate that this routine exposure to function reinforced students' functional understanding and aided them in generating functional models of similar quality throughout their education.

Students also demonstrated they had a strong disposition for enumerating low-level functions both in questions two and three of FunSkill as well as in their functional models. This is a feature inherent to functional models as unless they are black-box models, they describe the system at a greater level of detail, and entail more detailed or low-level functions. While these results from

Question 2 and Question 3 of FunSkill demonstrated students tended to enumerate low-level functions, they also generally captured the high-level overall system functionality for the system modelled. Given that the devices they were asked to abstract in these systems were relatively simple (a nail clipper and a generic dish washing apparatus), this propensity for low-level functions can largely be attributed to the fact that there is less high-level functionality for these simple straightforward systems. This simultaneous recognition of both high and low-level functions (as demonstrated in Figure 8), however, implies that students are in part exercising systems thinking skills by not only recognizing the relationships between components and sub-systems, but also by making note of the system organization and the relationship of a low-level function to the overall system's functionality (Hypothesis 2a and 2b). Unfortunately, students struggled to apply functional modeling conventions. While these models do appear to show high and low-level understanding, consistent assessment proved challenging.

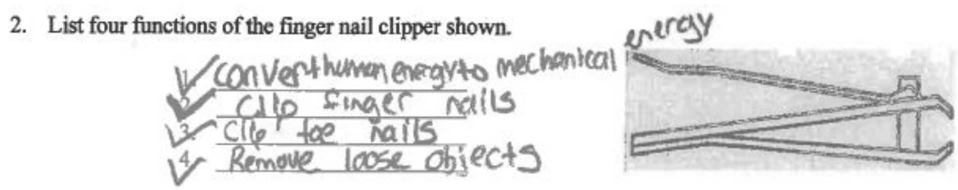

Figure 8: *An exemplar Question 2 from a Sophomore student displaying the inclusion of both high and low level functions.*

Above is an example response for Question 2 of FunSkill that highlights this observance of system organization and exhibition of systems thinking. This student recognizes the overall system functionality of the nail clippers provided, that being "Clip finger nails" and "Clip toe nails". This student also enumerates the low-level function "Convert human energy to mechanical energy" which is a sub-function that contributes to the overall system functionality they have already prescribed. Furthermore, this specific student has recognized that an operator has provided an input of energy into this system that is necessary for it to achieve its functionality.

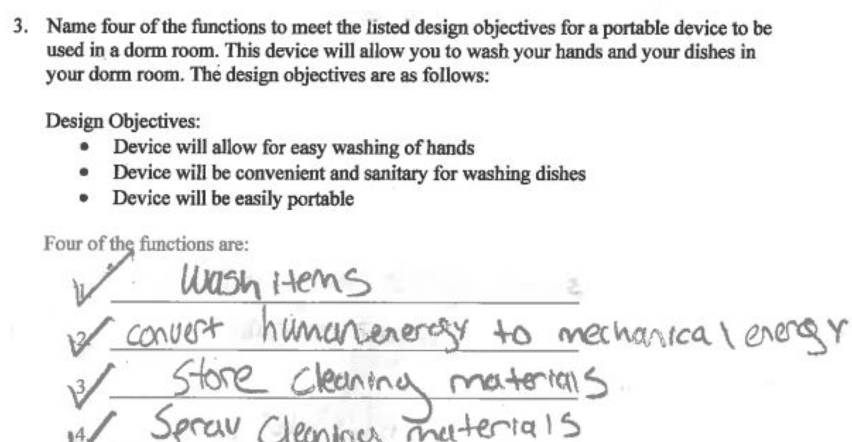

Figure 8: *An exemplar Question 3 from a Sophomore student that includes both high and low level functions.*

The same student's response to Question 3 highlights these systems thinking attributes as well, starting with a high-level function of "Wash items" then several low-level functions that are all functional components of that first function.

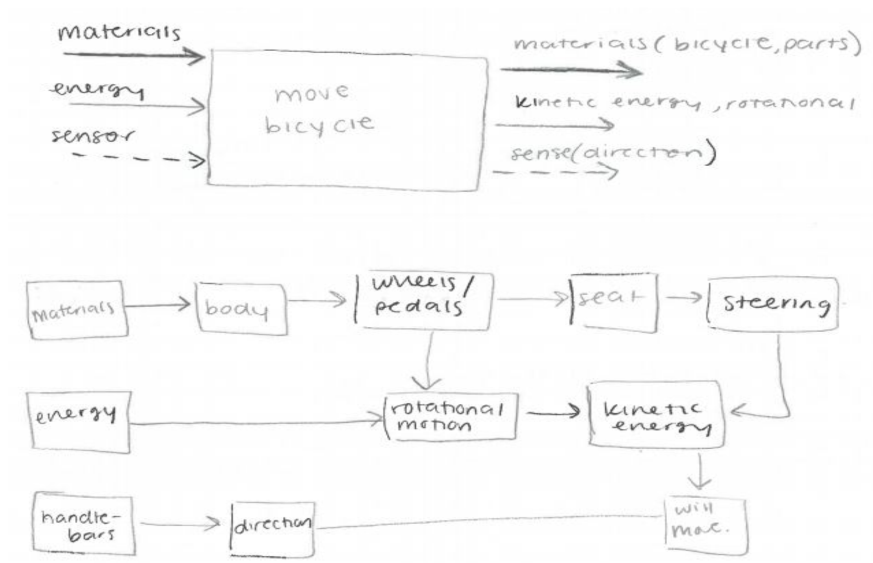

Figure 9: *A Question 4 response from a senior student that doesn't understand function or functional modelling.*

Figure 9 highlights the response of a student who exhibits some degree of systems understanding of the system they are analyzing but cannot communicate as they have not effectively retained their knowledge concerning the grammar rules and conventions associated with functional models. Their black-box model in particular conveys an understanding of the inputs and outputs to this system, and the conservation of them. Their functional model, however, is not comprised of functions, but of various components and energies that are relevant to the system. That being said, the inclusion of "seat" and "steering" in their functional model can be interpreted as a nod to the low-level functionality that those components achieve. Accordingly, had this student better understood the rules and conventions necessary to generate functional models, they may have perhaps displayed a systems understanding that was not captured by FunSkill and the corresponding scoring rubrics.

For system boundary and identification of input and output flows, no change was noted across the students (Hypothesis 2c and 2d). Further, students tended to score poorly on these questions.

7. Conclusion

These results mirror a previous study, where FunSkill results were compared between students who received functional modeling education, those who received a functional enumeration education, and a control [3]. In this prior study, researchers noted that students had a similar leaning towards low-level functions, but still usually included some high-level functionality. To include both overall system functionality, as well as the low-level functionality that contributes to the overall functionality of the system, indicates students are recognizing the organizational structure of the system and understanding that a variety of means are working together to allow the system to function effectively [3]. To recognize the relationships different parts of a system have with each other, and to recognize those parts' significance and relationship to the bigger system is at its core systems thinking [23]. Accordingly, while FunSkill was not explicitly designed to capture systems thinking skills, and in future work will need to be amended to hone in on such characteristics, we believe these results back prior research that suggests functional modeling and functional education is promoting a systems view amongst engineering students.

The lack of improvement through students' engineering education, however, does highlight the need for reform in functional modeling education and application as well as engineering education in general if we wish to better instill systems thinking qualities amongst undergraduate engineers. In our program, we have adjusted when, where, and how functional modeling is introduced to the students to help the students understand that function can capture systems at varying levels of abstraction. When the students who participated the study herein received instruction in function, instruction was re-enforced by a product tear-down activity following instruction in function, which we believe made function appear to be an abstraction that may be applied to a system. Now we perform product teardowns and then introduce function as a strategy for capturing the knowledge learned of systems, which includes hierarchical, boundaries, flows, and transformations. Our new approach then transitions into using function as a tool for new design from a tool for benchmarking. It remains too early to tell how this change has impacted student learning. What we do know, though, is that routine exercises with function have been shown to promote the retention of the knowledge necessary to generate functional models as well as to foster basic systems thinking skills, and consequently, teaching function remains a critical topic in our engineering curriculum.

Acknowledgements

The authors would like to thank all of the students for their voluntary participation in this study. This work is supported by the National Science Foundation through grants 1525170, 1525284, 1525449, and 1734519. In addition, this material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-1650044. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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