21ST INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED17
21-25 AUGUST 2017, THE UNIVERSITY OF BRITISH COLUMBIA, VANCOUVER, CANADA

TOWARDS ASSESSING STUDENT GAINS IN SYSTEMS THINKING DURING ENGINEERING DESIGN

Tomko, Megan (1); Nelson, Jacob (2); Linsey, Julie (1); Bohm, Matt (3); Nagel, Robert (2)
1: Georgia Institute of Technology, United States of America; 2: James Madison University, United States of America; 3: Florida Polytechnic University, United States of America

Abstract

Ultimately, as design educators we want to train our students to consider their world holistically such that they may recognize the interconnected elements of a system as well as synthesize and apply their engineering knowledge effectively when faced with new engineering challenges. The overarching goal of this research is to design both an assessment instrument and an assessment method to assess engineering students' ability to use systems thinking rather than recitation of memorized law or theorem. Toward this goal, the Systems Assessment Test (SysTest) is presented as an instrument for measuring systems thinking. Preliminary assessment measures for the instrument are presented along with results from an application during a sophomore design course where students taught functional modeling were compared to students taught function enumeration. The analysis demonstrates promise that the students taught functional modeling versus only being taught enumeration are using more of a systems thinking approach when approaching the SysTest design problem.

Keywords: Design education, Design learning, Systems Engineering (SE)

Contact:
Dr. Robert Lewis Nagel
James Madison University
Engineering
United States of America
nagelrl@jmu.edu

Please cite this paper as:
Surnames, Initials: *Title of paper*. In: Proceedings of the 21st International Conference on Engineering Design (ICED17), Vol. 9: Design Education, Vancouver, Canada, 21.-25.08.2017.

1 INTRODUCTION

During an undergraduate engineering education, students are continuously exposed to new theories, tools, techniques, and methodologies for analysis and experimentation. A student's ability to reason through unforeseen problems begs a key distinction over just processing new material. Ultimately, as educators, we want to know if students can think through a new challenge (i.e., can our students apply learned engineering knowledge to new open-ended, ambiguous problems). This is particularly important as we train engineering students for engineering work post-graduation.

The overarching goal of this research is to understand the impact learning to abstract functional knowledge during engineering design has on one's systems thinking ability during engineering design tasks. Through this study, one population of students are being taught functional modelling while a second group of students are not. Students at the sophomore level are being studied which allows for longitudinal study as the students in the cohort work to complete their engineering degrees. For the work presented herein related to systems thinking, **our working hypothesis is that students who learn to generate functional models versus list (or enumerate) functions will demonstrate more ability to apply systems thinking on an engineering design task.**

Toward this goal, this paper presents (1) the Systems Assessment Test (SysTest)—an open-ended design prompt that can be used to assess students' ability to think, in particular their ability to use systems thinking—and (2) the scoring approach taken to understand student responses to the SysTest prompt. The SysTest was crafted to be a design problem that prompts students to explore the solution space for a given design prompt as an open-ended response. The SysTest has been developed to be independent of functional abstraction and knowledge in an attempt toward broader applicability. Creating a clear and repeatable assessment for the SysTest required investigating thinking about systems which led to reviewing literature on systems thinking. Here we began extracting concepts, techniques, and definitions that resonated with the overarching goal of this research. This paper demonstrates the process made to date in making sense of systems thinking and how it applies to assessing an open-ended design problem.

2 SYSTEMS THINKING

In its' origin, systems thinking remained generally defined and free to further clarification. Systems thinking represented a continuum that shifted from viewing and perceiving the nuts and bolts of a system (i.e., equations and simulations) to the system in its totality (Richmond, 1991). While this left room for clarification, additional definitions have sprouted up in order to reconcile the loosely termed concept. Even more so, the concept has been analysed through the lens of systems engineering, systems dynamics, and psychology (Whitehead et al., 2015; Vanasupaa et al., 2008; Kordova et al., 2015; Arnold and Wade, 2015; Caulfield and Maj, 2001). As such, all these lenses have crafted and formed a greater understanding of systems thinking. Nevertheless, it is also important to note that systems thinking is not to be confused with thinking systematically. Systems thinking is seeing the interactions and relationships that reinforce the system as a whole. Systematic thinking is simply thinking logically and methodically about a system. Systems thinking focuses on describing and understanding a system, while the systematic thinking focuses on the process of thinking about a system. Overall, systems thinking looks to enhance how a person conceptualizes and negotiates the complexity of real world phenomenon (Chan, 2015).

2.1 Systems Thinking Competencies and such overview

Because systems thinking remains openly defined, numerous scholars have pursued defining systems thinking, and toward this definition, a wide variety of competencies, skills, assets, etc. that are most relevant to systems thinking, or in some cases systems engineering, have been crafted.

Systems thinking is considered to be one of five learning disciplines that can be utilized to transform companies into a learning organization (Senge, 1990). In this capacity, systems thinking facilitates the progress of four disciplines: personal mastery, mental models, shared vision, and team learning (Senge, 1990; Sage, 1995). These disciplines unearth the skills that create synergy and excellence in a learning organization, ultimately shaping an organization where systems thinking transcends individual thinking and captures the whole perspective of the organization. Efforts to expand on Senge's principles for systems thinking to that of engineering systems thinking led researchers to develop thirty engineering systems thinking laws. Some of which include: considering the customer, implications, non-engineering solutions, multiple perspectives, future projections and modifications, multiple working solutions, trade-offs, the whole and the interactions of a system's elements, and external interactions (Frank, 2000).

In one vein of literature, system competencies and systems thinking inhibitors forecast why systems thinking is not a natural act—people approach only the surface of problems and become overwhelmed by the increasing complexity of systems through analysis (Valerdi and Rouse, 2010). The systems thinking competencies weave the ability to define "universe" accordingly, define overall system accordingly, see relationships, see things holistically, understand complexity, communicate across disciplines, and take advantage of a broad range of concepts, principles, models, methods, and tools (Valerdi and Rouse, 2010). If a student has these abilities, then they are using systems thinking to solve a problem. The systems thinking inhibitors, however, must be considered and admit to the following: over-specialization, short time horizon, personality traits, institutional constraints, a combination of factors, and educational system (Valerdi and Rouse, 2010).

Various frameworks advocate for what comprises systems thinking. In one framework, systems thinking is managed by four foundations to systems methodology: holistic thinking, operational thinking, systems theories, and interactive design (Gharajedaghi, 2011). Another framework moulds the different perspectives of systems thinking that pertain to engineering and fashions the foundational concepts that are considered useful towards successful design: boundary, part-whole structure, function and behaviour, non-functional properties, determinism, feedback and system dynamics, analysis vs synthesis, conceptual models, and adaption and learning (Chan, 2015). These core concepts would be incomplete without recognizing that systems thinking encompasses both a human aspect and technological aspect (Chan, 2015). In other words, we, as engineers and designers, must think of both the human relations to our system and the technological development of the system. For example, creating a state-of-the-art cellular phone may not have a user-friendly interface, thereby neglecting the human aspect to the system.

Furthermore, additional research investigates the skills or attributes that embody systems thinking and system thinkers. For one, research deems that there are seven critical skills of systems thinking: dynamic, closed-loop, generic, structural, operational, continuum, scientific (Richmond, 1993). Seeing that this particular research emanates from the work of the researcher who coined the term "systems thinking" then more regard is placed on these attributes. Elaborating on these skills and recognizing the value that systems thinking would have in project management, systems engineers were evaluated based on their ability to take an engineering systems thinking approach (Frank et al., 2011). System engineers with a high Capacity for Engineering Systems Thinking (CEST) were noted to practice the following: analysing customer needs and requirements; developing the concept of operation; conceptualizing the solution; generating a logical solution (functional analysis) and a physical solution (architecture synthesis); using simulations and optimization; implementing systems design considerations and conducting trade studies to generate alternative solutions (Frank et al., 2011). This high capacity for engineering systems thinking regularly appeared as a personality trait among the participants. These personal behaviours of systems engineers who are highly regarded in their work can also be labelled under five categories: leadership skills; attitudes and attributes; communication, problem solving and systems thinking; and technical acumen (Frank et al., 2011). Under the problem solving and systems thinking domain fall additional attributes: identifies real problem; assimilates, analyses, and synthesizes data; finds connections and patterns; sets priorities; keeps focus on mission requirements; has creative and problem solving abilities; validates facts, information, assumptions; remains open minded and objective; draws on past experiences; manages risk (Derro and Williams, 2009). Evidently, many qualities are attributed to effective systems thinking. While the lists seem to continuously tack on more qualities, these traits help to identify what makes someone a good systems thinker, and of particular interest for this research, what makes students good systems thinkers. These qualities designate how educators can view and assess the progress of their students in the classroom.

Recognizably so, certain concepts transfuse throughout the literature. Many researchers investigate what makes systems thinking a valuable ability and how this ability can be defined, articulated, and utilized. While the literature continues with more traits and ways to make meaning of systems thinking, the aforementioned research findings introduce an adequate allowance for crafting a thread of similarity that can support our efforts to create and assess an open-ended design problem aimed at procuring the students to think.

3 SYSTEMS ASSESSMENT TEST (SYSTEST)

It seems, based on a review of the literature, that the attributes, competencies, etc. of systems thinking may be beyond the abilities of an undergraduate engineering student—at least during their first years as an engineering student. Consequently, a student's efforts are likely to just scratch the surface of systems thinking and cannot be completely defined through the frameworks outlined in literature. This leaves one to wonder, though, what is the root of systems thinking? One might conjecture based on literature that systems thinking may manifest itself as simply being able to identify the elements of the "system" that interplays with the device being designed. For example, if designing a riding unit that carries a small child for a bicycle, one might choose to focus only on specific components of the riding unit (a narrow system view) or one may realize the need to understand the road, the environment, the bike that the unit is coupled to, the person who typically provides the propulsion, the child in the carrier, etc. In other words, perhaps being a systems thinker is about being able to question the assumptions given, understand the problem through a different lens, and expand the boundaries of the solution space? Still, it is necessary to determine how one could apply this insight into assessing the student responses to an open-ended design prompt.

Toward this understanding of literature, the Systems Assessment Test was developed to build off of the competencies and attributes of the systems thinking literature. More specifically, the SysTest was designed to cause students to think through the problem using a holistic approach, a process that results in a logical solution, and view of a problem, and seeing the connections and patterns within a real problem (Derro and Williams, 2009; Frank et al., 2011; Valerdi and Rouse, 2010). This resulted in a problem that was situated in a real-life scenario, remained open-ended, and did not articulate a specific path to solving the problem.

3.1 Design Problem

The SysTest prompts students to consider an abstract problem statement rather than explicitly asking the students to use a specified design tool, e.g., a functional model, for crafting a solution to a design problem. Students are given a blank sheet of paper to compose a response for how they would describe the system using techniques learned in prior courses. Figure 1 provides the SysTest prompt.

> Read the following customer needs statement and then describe the system as best as possible using technique(s) you have learned.
>
> *A company wants to develop a new automated system for lawn debris (such as tree leaves) collection. The company believes (based on the success of home vacuuming robots) that there is a niche market for automated lawn debris collection systems that a homeowner can use instead of manually raking their own lawn. For this product to be viable in the market, the company believes that the system must fully replace traditional manual raking, must be fully automated, and must be simple to install and maintain. To simplify disposal, the system must include a mechanism to grind and compress all collected debris.*

Figure 1. Systems Assessment Test (SysTest)

3.2 SysTest Assessment Approaches

The student responses to the SysTest varied greatly due to the open-ended prompt. Initial efforts to assess the SysTest resulted in developing two different frameworks (based on student responses and our understanding of systems thinking literature) that would allow for categorizing the variety of features within the student responses: the Taxonomy Approach and the Spectrum Approach, see Figure 2. Individually and simultaneously, the two approaches were pursued to design potential frameworks. In the Taxonomy Approach, the student responses were the foundation for the framework. Identified throughout the student responses, four levels of systems thinking resonated in the students' work: (1) Holism – considering all system inputs and outputs, as well as interaction between sub-systems, and using multiple useful models and understanding that different models offer different insight; (2) Modelling – applying some form of modelling of the system, functional or otherwise; (3) Functional Thought – using function in lieu of components to explain the system; and (4) Intuition – forming a loose idea for a design based on and explained primarily via components.

The Taxonomy Approach, developed from the student responses for the SysTest, demonstrates that student responses had a level of intuition which increased in systems through functional thought, modelling, and holism. Intuition is based on the student responses neglecting to use known design process techniques. Functional thought is introduced when students began to recognize the functions and roles of the system. Furthermore, when the students produce a model, this demonstrates abstract thinking regarding the system. Finally, the holistic view of the system becomes evident in student responses when they articulate the overall purpose of the system, recognize relationships and interconnections, and apply multiple techniques to design their solution.

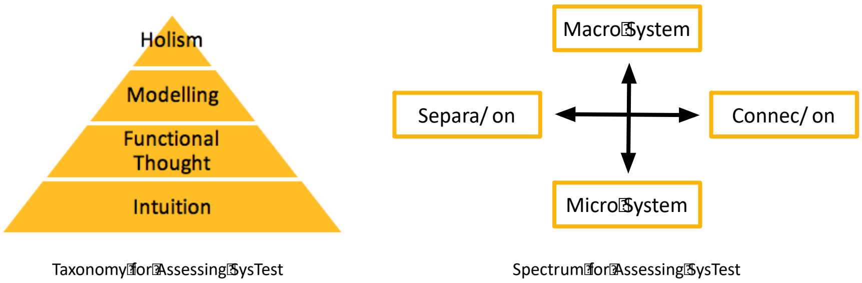

Figure 2. Approach 1 – Taxonomy for assessing SysTest and Approach 2 – Spectrum for Assessing SysTest

To demonstrate, Figure 3 shows a regenerated student's response where the student (1) intuitively starts with extracting objectives from the problem, (2) proceeds to extrude function and create a black box model, (3) generates and analyses potential ideas through a Pugh chart and decision matrix where the analysis is based on intuition of the ideas but also modelled in a logical process, (4) sketches the final physical model of the system, and (5) holistically captures the both technical specs of the system to the overarching purpose of the system.

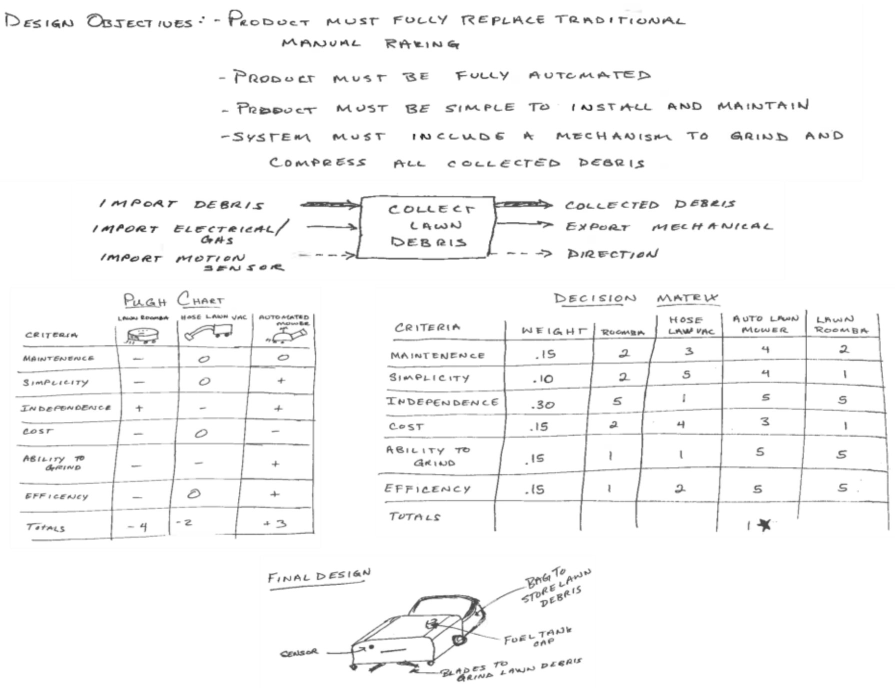

Figure 3. Regenerated example of a solution that has intuition, functional thought, modelling, and holism

The Spectrum Approach was developed solely on the literature and captures the relationship between viewing the overall system and connections verses focusing on the details and elements of the system separately. This results in a spectrum view of systems thinking that divides holism into two dimensions, via a systems view and connection view: (1) Macro system: "big picture" view of the system; (2) Micro system: "in the details" view of the system; (3) Separation: seeing system parts separately; and (4) Connection: seeing the connections and relationships between system parts.

In the Spectrum Approach, a student response could demonstrate a form of either reductionist thinking or expansionist thinking. A reductionist thinker first orients a system by the big picture and connections of a system and then proceeds to separating the system and understanding the elements of the system (Chan, 2015; Broekstra, 2014). Expansionist thinking, however, begins with the elements and separated systems and then proceeds to understand the connections and the big picture of a system (Broekstra, 2014). Along the devised spectrum, both forms of thinking seem possible. This spectrum, however, proved limited in the ability to capture all of the features, attributes, and dimensions of systems thinking, e.g., the human dimension and technical dimension, and consequently, examples could not easily be identified from the student work.

Still, the literature provided potential to map characteristics of systems thinking in the student responses to Bloom's revised taxonomy (Hopper, 2007). These characteristics start with recognizing interconnections, succeeded by identifying feedback, understanding dynamic behaviour, differentiating types of variables and flow, using conceptual models, creating simulation models, and testing policies (Hopper, 2007). A quick look into this literature and juxtaposing it against the student responses revealed that recognizing interconnections was a great accomplishment for students—if they were able to achieve this. Unfortunately, though, recognizing interconnections is the lowest order of thinking in Hopper's taxonomy—perhaps, though, this is the seed of systems thinking? Nevertheless, working through the different frameworks aided in the development of a coherent list of themes and attributes of systems thinking that would be relevant to the level of expertise for sophomore engineering design students.

4 METHODOLOGY

4.1 Participants and Administration

At a comprehensive, East Coast university in the United States, across four sections of a sophomore engineering design course, seventy-nine students provided consent for participation in this study. Of those four sections, the two Tuesday sections were assigned to the Modelling group where the students were taught functional modelling and functional enumeration, and the two Thursday sections were assigned to the Abstraction group where the students were only taught function enumeration and not taught functional modelling. Functional modelling and enumeration as taught are defined below.

- **Functional Modelling** based on the function/flow generative modelling approaches described by Pahl and Beitz (1984) uses functions to represent the transformations of flows (energies, materials, and signals) required for system operation. Functional modelling, as taught to the students, requires to levels of modelling: a black box describing the entire system and a sub-functional model describing the transformations of the input flows to output flows defined by the black box. Students are provided with the algorithmic approach for generating functional models developed by Nagel and Bohm (2012) as well as the Functional Basis developed by Hirtz et al. (2002).
- **Functional Enumeration** as taught is the process of considering and listing all function/flow pairs (high-level and low-level) required for system operation as a technique for abstracting system operation into discrete, form-independent statements (Dym and Little, 2009). Enumerated functions are often generated at a system, sub-system, and component-level.

All four class sections were provided with similar instruction in other design techniques including: interviewing, requirements identification, persona generation, concept generation tools (e.g., 6-3-5), and design refinement tools (e.g., decision matrices). All students were expected to be of similar background prior to enrolment in the course with their only prior engineering course having been two introductory engineering courses completed during the prior academic year, and neither course included content on functional abstraction. All students were enrolled in a non-discipline specific engineering program on track to earn a Bachelor of Science in Engineering. No incentives were offered to the participants. Lesson plans for both the Modelling group and the Abstraction group follow.

Modelling Group Lesson Plan for 100-minute class period:

- First (~30 minutes), students learned about system abstraction which included identifying a system boundary, sub-systems, components, and flows. An engineered system was used as an example during class with a discussion on system breakdown and perspective being the driving factors for system abstraction choices.
- Second, (~10 minutes), the students learned about function enumeration which included a discussion that function is a translation of design objectives, is comprised of a verb-noun pair, describes what a system, sub- system, or component does, and is form independent. Examples of a bicycle, music player, lawn mower, electric motor, and toothbrush were used during class for both

groups. For these example systems, students identified functions for the system during class, and student responses were discussed.

- Third, students learned to generate functional models. Students were talked through an example functional model during the lecture portion of the course (~20 minutes), and during the active learning portion of the course, students, as teams of four, worked through an example functional model during class (~40 minutes). All students were provided with a step-by-step example, students were provided the following four steps annotated with an example black box and/or functional model developed to a level appropriate for each step.
- As homework, students in the Modelling group generated black box and functional models first independently for a bicycle.

Abstraction Group Lesson Plan for 100-minute class period:

- First (~30 minutes), students learned about systems abstractions which included identifying a system boundary, sub-systems, components, and flows. Both an engineered system and a natural system were used as examples during class with a discussion on system breakdown and perspective being the driving factors for system abstraction choices. Students worked in-class examples as groups to understand the process (~60 minutes).
- Second (~10 minutes), the students learned about function enumeration which included a discussion that function is a translation of design objectives, is comprised of a verb-noun pair, describes what a system, sub- system, or component does, and is form independent. Examples of a bicycle, music player, lawn mower, electric motor, and toothbrush were used during class for both groups. For these example systems, students identified functions for the system during class, and student responses were discussed. No further discussion of function was provided for the Enumeration group.
- As homework, students in the Enumeration group generated abstracted systems for a bicycle.

The SysTest was administered as a part of all students' final examination during the final exam time period as scheduled by the university. The final exam period was two hours, and students completed the question with all other final exam questions. The exam took most students the entire two hours.

4.2 Hypothesis

Students in the Modelling group will demonstrate more ability to apply systems thinking on an engineering design task when compared to the Abstraction group.

4.3 Categorizing Student Responses

Over the course of one semester, three researchers (one professor in functional modelling, one graduate researcher, and one undergraduate researcher trained in functional modelling) examined the student responses for systems thinking. Since the SysTest was not evoking the direct evidence of systems thinking as intended, the student responses were categorized based on the different techniques that the students were using, see Table 1. While developing these categories, a recurrent challenge arose from trying to understand how much thought the students put into their solutions, systems thought or otherwise. Some students had more thorough and detailed responses than other students, even though a majority of responses, thorough or otherwise, focused on components of a system. It seemed that the students who had more thorough and detailed responses explored more of the solution space and would achieve a higher level on Bloom's taxonomy, potentially "understanding" (Hopper, 2007). On the contrary, students who restated the prompt did not even manage to "remember", regardless of whether they used requirements, components, process, or even function. This almost assumed that there was another dimension to the techniques: thought level. How to pursue such a metric remained unclear, and it was estimated that if a student is able to produce a higher order solution, i.e. a functional model, then that was enough to show systems thinking (holistic view) in order to create the functional model. They could not merely create a functional model from memory seeing as they had not been given the design problem before. Therefore, categorizing the techniques that students use provides an appropriate first pass analysis for student responses; see Table 1 for the list of techniques. The list of techniques was generated based on design knowledge that had been taught to students throughout the semester as well as content that students should have learned in prior engineering and physics courses. Following initial generation of the techniques list, the list was iterated, trimmed, and expanded based on techniques that were actually used by students when completing the SysTest.

Table 1. Techniques used in student responses and key for analysis with yes/no questions

Key	Techniques
1	Functional Model
2	Black box
3	Functions
4	Design objectives and/or constraints
5	Design specs
6	Design idea(s)
7	Repeats question
8	Design process
9	Pugh Chart
10	Decision Matrix
11	Picture of Product
12	Morph Matrix
13	Benchmark tree
14	System, subsystem, or components
15	Physics laws
16	Bio-inspired
17	No attempt

Key	Yes/No Questions
18	Follow design process?
19	Derive abstraction?
20	Jump to first solution?
21	Gives potential ideas?
22	Define objectives, functions, or constraints?
23	Use multiple techniques?

The conditions were compared and examined based on the number of students who used different techniques. Differences regarding the techniques that the students used led to analysing the data based on yes/no questions, also provided in Table 1. The yes/no questions provide more context for the list of techniques and were generated off of recurring situations that we say in the student responses. Moreover, the yes/no questions were answered through examining the techniques for each student and tallying yes or no (1 or 0) for the corresponding questions. These yes/no questions and the techniques were then statistically analysed for significance.

4.4 Analysis

Initially, a graph was produced to view the percentage of students who used each technique along with the percentage of students who received a 'yes' affirmation for each yes/no question, see Figure 4 for the graph and Table 1 for the key. This allowed for a quick understanding of the techniques used across groups. This analysis shows that the students in the Modelling group are more inclined to generate a functional model and black box, while the Abstraction group produced more functions and utilized the system, subsystems, and components technique more than the Modelling group. The Modelling group also demonstrates a higher application of the engineering design process and deriving an abstraction.

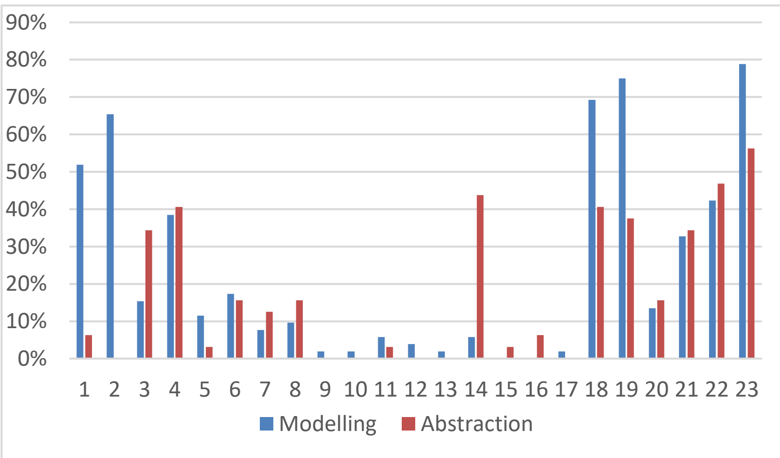

Figure 4. Graph of percentage of students who used techniques and with 'yes' affirmations

To assess the significance of differences between Modelling and Assessment groups across the 17 categories and the 6 yes/no questions, a binary logistic regression analysis was completed in IBM SPSS Statistics v24, see Table 2. Each of the techniques that were used by the students and the tallied binary answers to the yes/no questions were designated as outcome variables for the analysis.

Table 2. Chi-squared analysis for techniques that students used in their responses

	χ^2 (1, N=84)	p-value
Functional Model	**21.294**	**0.000**
Black Box	**46.299**	**0.000**
Functions	**3.985**	**0.046**
Design Objectives or constraints	0.039	0.844
Design Spec	2.095	0.148
Design Ideas	0.041	0.841
Repeats Question	0.518	0.472
Design Process	0.665	0.415
Pugh Chart	0.967	0.326
Decision	0.967	0.326
Picture of the Product	0.323	0.570
Morph Matrix	1.948	0.163
Benchmarking Tree	0.967	0.326
System, subsystem, or components	**17.82**	**0.000**
Physics law	1.950	0.163 *only 1 student in Abstraction
No attempt	3.940	0.047 *only 2 students in Abstraction
Follow Design Process?	**6.682**	**0.010**
Derive abstraction?	**11.739**	**0.001**
Jump to first solution?	0.075	0.784
Give potential ideas?	0.025	0.874
Define objectives, functions or constraints?	0.167	0.682
Use multiple techniques?	7.805	0.099

The analysis further validates the initial findings evaluated in the percentages. The analysis shows that the Modelling group is more likely to draw a functional model (χ^2 (1, N=84)=21.29, p<0.001), include a Black Box (χ^2 (1, N=84)=46.29, p<0.001), follow the design process (χ^2 (1, N=84)=0.66, p=0.41)and derive an abstraction (χ^2 (1, N=84)=11.73, p=0.001). Additionally, the Abstraction group is more likely to focus on extracting functions from the SysTest (χ^2 (1, N=84)=3.98, p=0.046) and utilizing systems, subsystems, and components (χ^2 (1, N=84)=17.82, p<0.001).

5 DISCUSSION

The SysTest was designed to assess students' abilities beyond recitation to apply a systems thinking approach, incorporate different techniques learned through lectures and homework, follow a process to craft potential solutions, and generate an abstract system model to increase problem understanding.
Students' abilities to utilize systems thinking were assessed through the techniques applied in their SysTest responses and assessment based on the yes/no questions. Students' responses were analysed and framed according to the overall scope of this work which is to see if teaching functional modelling is impacting students' ability "to do" design with the goal of understanding, in the context of the SysTest, how students are utilizing systems thinking and how this compares between students taught functional modelling versus function enumeration. It was hypothesized that teaching functional modelling would enhance a student's ability to apply systems thinking. The analysis demonstrates that students who are taught functional modelling do follow the design process and derive abstractions more than students only taught function enumeration. Further, we see that this Modelling group was more likely to apply multiple modelling design techniques than students in the Abstraction group. Taken together, this indicates that students in the Modelling group are perhaps better able to synthesize the techniques

learned during the semester toward representing a new system design. This provides promise that the students in the Modelling group are using more of a systems thinking approach when approaching this design problem because they are capturing the details of the system through the design process while also abstracting the system. This should be investigated further. Unfortunately, the SysTest used in this study did not measure students' previous knowledge, and the remains an unknown for future analysis.
Interestingly, students in the Modelling group generated less functions, though, than students in the Abstraction group. This indicates that perhaps there is an inverse relationship between general enumeration of functions and functional model generation. Perhaps students in the Modelling group feel better able to describe the system through the application of modelling techniques learned during class? Or, perhaps we are seeing that the enumeration group is generating duplicate functions to arrive at quantity over quality? This too should be investigated further.
Further assessments require a more sophisticated approach to assessment perhaps employing a grounded theory approach to rubric development for student response assessment. Initial results, however, do show that by teaching functional modelling, students appear to become better systems thinkers.

REFERENCE

Arnold, R. D. & Wade, J. P. (2015), A definition of systems thinking: A systems approach. *Procedia Computer Science,* 44**,** 669-678.

Broekstra, G. (2014), *Building High-Performance, High-Trust Organizations: Decentralization 2.0,* New York, Palgrave Macmillan.

Caulfield, C. W. & Maj, S. P. (2001), A case for systems thinking and system dynamics. *IEEE International Conference on Systems, Man, and Cybernetics,* 2001 2001. 2793-2798.

Chan, W. T. (2015), *The role of systems thinking in systems engineering, design, and management*.

Derro, M. E. & Williams, C. R. (2009), Behavioral competencies of highly regarded systems engineers at NASA. *IEEE Aerospace conference,* 7-14 March 2009 2009. 1-17.

Dym, C. L. & Little, P. (2009), *Engineering Design: A Project-based Introduction,* Hoboken, John Wiley & Sons, INC.

Frank, M. (2000), Engineering systems thinking and systems thinking. *Systems Engineering,* 3**,** 163-168.

Frank, M., Sadeh, A. & Ashkenasi, S. (2011), The relationship among systems engineers' capacity for engineering systems thinking, project types, and project success. *Project Management Journal,* 42**,** 31-41.

Gharajedaghi, J. (2011), *Systems thinking: Managing chaos and complexity: A platform for designing business architecture*, Elsevier.

Hirtz, J., Stone, R., Mcadams, D., Szykman, S. & Wood, K. (2002), A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts. *Research in Engineering Design,* 13**,** 65-82.

Hopper, M. A. (2007), *Proposing measures for assessing systems thinking interventions.* Master of Science in Environmental Science, University of Nevada Las Vegas.

Kordova, S. K., Ribnikov, G. & Frank, M. (2015), Developing systems thinking among engineers: Recent study findings. Systems Conference (SysCon), 9th Annual IEEE International, 13-16 April 2015 2015. 50-53.

Nagel, R. L., Bohm, M. R., Cole, J. & Shepard, P. (2012), An Algorithmic Approach to Teaching Functionality. *ASME 2012 International Design Engineering Technical Conferences.* Chicago, IL: ASME.

Pahl, G. & Beitz, W. (1984), *Engineering Design: A Systematic Approach,* London, Design Council.

Richmond, B. (1991), Systems thinking: Four key questions. High Performance Systems, Inc.

Richmond, B. (1993), Systems thinking: Critical thinking skills for the 1990s and beyond. *System Dynamics Review,* 9**,** 113-133.

Sage, A. P. (1995), *Systems management for information technology and software engineering,* John Wiley & Sons, Inc.

Senge, P. M. (1990), *The fifth discipline: The art and practice of learning organization,* New York, Doubleday/Currency.

Valerdi, R. & Rouse, W. B. (2010), When systems thinking is not a natural act. 4th Annual IEEE Systems Conference, 5-8 April 2010 2010. 184-189.

Vanasupaa, L., Rogers, E. & Chen, K. (2008),Work in progress: How do we teach and measure systems thinking? 38th Annual Frontiers in Education Conference, 22-25 Oct. 2008 2008. F3C-1-F3C-2.

Whitehead, N. P., Scherer, W. T. & Smith, M. C. (2015), Systems thinking about systems thinking: A proposal for a common language. *IEEE Systems Journal,* 9**,** 1117-1128.

ACKNOWLEDGMENTS

This work is supported by the National Science Foundation through grants 1525449, 1525170, and 1525284. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of National Science Foundation.