An Experiential Approach to Understanding the Engineering Design Process

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***Abstract*—This paper presents the analysis of engineering design process representations produced by a group of K-12 science teachers and first-year college students. Both groups were relatively new to engineering design and created the representations following their completion of a design challenge where they built a prototype of a tropical rain forest tower using straws and other fasteners. The paper includes a description of the design activity and a discussion of the similarities and differences between the representations produced by the two groups. The analysis is expected to provide insights on how introductory design activities can shape learners' understanding of the engineering design process.**

Keywords— engineering design process, K-12 teachers, NGSS

I. Introduction

The engineering design process is best taught using active learning techniques rather than rote methods [1], [2]. By first engaging in a design challenge, followed by guided reflection, students can learn the concepts and related mindsets associated with design thinking. One activity that has been successfully used to introduce students to the engineering design process is the tower of straws challenge [3], [4]. In teams, students are provided with a fixed number of straws and fasteners and are instructed to build a structure as tall as possible, within a limited amount of time. Given the context of the challenge, additional requirements or constraints can be added, such as the tower must support a minimum load or be constructed using the least amount of materials. The scope of the activity is well defined, allowing for the entire engineering design process to be accomplished, with iteration, within a short period of time.

The tower of straws challenge was adapted and used as an introductory activity with a group of science teachers attending a week-long professional development (PD) training. The focus of the PD was to deepen the teachers' conceptual understanding of the Next Generation Science Standards (NGSS), which now integrates engineering design into the structure of K-12 science education [5]. The incorporation of engineering design is one of the more unfamiliar aspects of the new standards, and a significant portion of the training was dedicated to enhancing the teachers' understanding of it. For many of the teachers, the tower of straws challenge was their first formal introduction to, or engagement in, engineering.

This paper presents the teachers' derived understanding of the engineering design process based on the graphical models they produced to represent the process they used to complete the tower challenge. These models are compared to those created by first-year college students in an introductory engineering course who also completed the same tower of straws challenge at the beginning of the semester. The paper also includes a discussion of the similarities and differences between these two groups, i.e., science teachers and first-year college students, in terms of their understanding of the engineering design process and the possible implications of this understanding on their future learning of and engagement with the topic.

II. Introducing Science Teachers to NGSS and Engineering Design

A. *Professional Development Training*

The Science Engineering and Technology (SET) Project (*http://thesetproject.weebly.com/*) is a 3-year grant funded by the federal and state government through a program called the California Math and Science Partnership (CaMSP). The project seeks to bring engineering and technology to the forefront of science education by helping to transition teachers from the old state standards to NGSS. The implementation plan for the SET project involves developing and offering a series of PD trainings over the duration of the grant. These trainings will ultimately prepare the cohort of participating teachers to design, develop, test and revise new instructional units and guides based on NGSS. The first installation of PD sessions occurred over 5 consecutive days during summer 2015 and focused on introducing teachers to the NGSS framework, engineering design, and various technology applications that could be used to enhance science learning in the classroom.

The cohort of participants in the SET project comprised 73 science teachers, representing three school districts in Southern California. The majority of the group teaches physical sciences, earth sciences or life sciences at either middle or high school, with a few coming from elementary schools. Many of the teachers had no prior experience with engineering or engineering design prior to the PD.

B. Introductory Engineering Design Activity: Tropical Rainforest Tower Challenge

The introduction to engineering was done on the first day of the training and also served as an icebreaker activity. Led by two engineering professors, the teachers were presented with the following scenario:

Forests, especially tropical forests, are one of the most important sinks of carbon on the planet. They, however, respond to climate change—whether it is temperature increase or changes in precipitation. These responses may have profound effects on their ability to continue to absorb carbon from the atmosphere. To monitor the environmental changes of the rainforest, a systems ecologist, working on a limited budget, needs to build a tower to support environmental monitoring equipment in the canopy of a rainforest in tropical Brazil.

The tower needs to support at least 2500 lbs., of people and equipment combined, but no more than 5000 lbs. The monitoring equipment functions best the higher up it is in the canopy region, which ranges between 98 ft. – 148 ft.

Based on the presented scenario, the teachers were challenged to work in teams of 3 to build the tallest possible prototype tower in 25 minutes to support a load of 25 - 50 marbles, using the least amount of materials from a provided prototype supply kit. The contents of the kit are identified in Table 1 along with the real-world equivalents for each item. An inch in the prototype tower was equated to 6ft in the real-word.

Table 1. Contents of prototype kit

Prototype Supply Kit	
Provided Materials	***Real-World Representation***
1 marble	100 lbs.
Red Straw	Building Material | Cost = $1,000
Translucent Straw	Building Material | Cost = $500
Paper Plate (to only be used at the base)	Foundation
Modeling clay	Binding material
Paper clips	

The tower of straws challenge is a popular introduction to engineering design activity. It has been used at the K-12 level as well as in first-year engineering courses [3]. In many of the past implementations of the activity, including those led by one of the engineering professors that co-facilitated the activity during the PD training, no direct real world connection is made. Students seem to be asked to build a tower for no specified reason other than to complete the task. When asked to reflect on the authenticity of the challenge, some of the student responses identified the lack of real world application as a flaw in the activity that diminished the experience. For the PD training, this common omission was addressed by connecting the challenge to the real need of a systems ecologist. This modification was important given that in NGSS [5], engineering practices, particularly those related to design, are incorporated to make students' knowledge of science more meaningful and relevant.

A

B

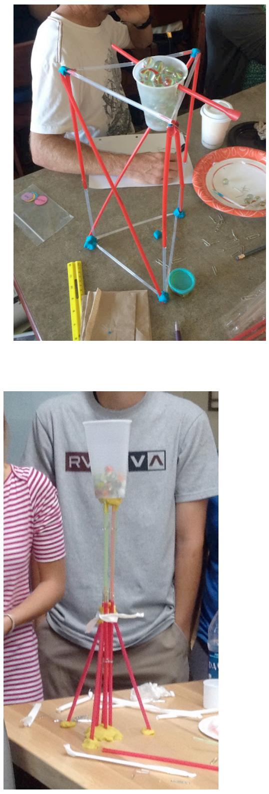

Fig. 1 Tower built by one of the teacher teams (A) and one of the first-year student teams (B)

C. Post Activity Reflection

In the PD training, each team produced a tower at the end of the allotted time. Using the following evaluation criteria: height (45%), load (35%), and cost (20%), a performance score for each team was calculated to determine which designs best met the needs of the systems ecologist. Following the design evaluation, the teachers were introduced to 5 terms (listed in alphabetical order) that are used to articulate steps in the engineering design process, along with a description of each word. The terms were taken from the model of the engineering design process that was developed for the Engineering is Elementary (EiE) series [6], [7]. Each teacher was then given 5 cards, with each term on a separate card, and two blank cards. In the same teams that were formed to complete the tower challenge, the teachers were asked to use their collective cards to produce a graphical representation of the process they used to complete the tower activity. The blank cards could be used to define a step not described by any of the 5 provided terms.

After a brief discussion of the various EDP representations produced by the teachers, the facilitators presented the EiE model and discussed its significance highlighting features such as the order of the steps and the circular or iterative nature of the process.

TABLE 2. Engineering Design Process (EDP) Terms with Descriptions

EDP Step	Description of Step
Ask	What is the problem? How have others approached it? What
Create	Follow your plan and create something. Test it out!
Imagine	What are some solutions? Brainstorm ideas. Choose the best
Improve	What works? What doesn't? What could work better? Modify
Plan	Draw a diagram. Make lists of materials you will need.

III. Post-Analysis of the EDP Representations

There were time constraints during the PD training that did not allow for a deep review of the individual EDP representations produced by the teachers. However, all the representations were collected and reviewed later by a team of 5 researchers who sought to understand how these representations can be used to evaluate how the tower challenge shaped the teachers' understanding of the engineering design process.

In Fall 2015, the Tropical Rainforest Tower challenge was repeated with a group of 69 first-year college students who took an Introduction to Engineering course with the professors that facilitated the activity at the PD training. The same procedure used with the teachers was followed with one exception: the students received 7 terms from the TeachEngineering initiative to articulate the steps in the (https://www.teachengineering.org/engrdesignprocess.php) engineering design process. The 7-step process includes the 5 given to the teachers from EiE and two others. The additional 2 steps were: Research - *How have others approached it? What solutions currently exist?* and Test - *Test and evaluate what you created. Does it work? Does it solve the need?* The teachers only received 5 steps because that model was more applicable to the middle and high school students they will be teaching. 'Research' and 'Test' were encompassed within the 5 steps provided, but not explicitly identified. For the first year college students, the model explicitly included the two extra steps so that the students would be able to continue to reference that model throughout their undergraduate college career. The EDP representations created by the student teams were collected and analyzed along with those from the teachers. Given that both groups, i.e., science teachers, and first-year college students, had little to no prior experience with engineering design, the research team expected to see few differences with respect to the steps followed and the sequence of execution. However, given the similarities between the scientific method and the engineering design process, the research team expected to see more evidence of iteration in the representations produced by the teachers.

IV. Methods

Sixteen EDP representations were collected from the teacher teams and 17 from the first-year student teams. Each representation was copied into pdf format. In this version of the data, all identifying information was removed and a unique identifier was added to each one. The data was then stored on a shared drive so each researcher could have access to them. Fig. 1 shows an example of an EDP representation from both groups.

A

B

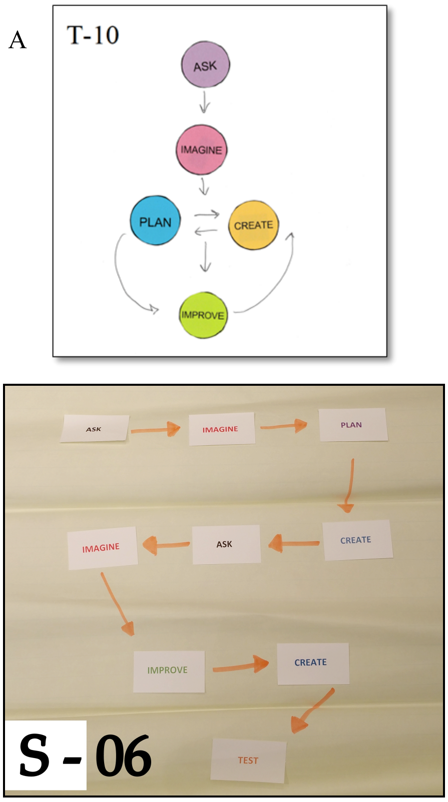

Fig. 2 EDP representations from one of the teacher teams (A) and one of the first-year student teams (B)

A combination of qualitative and quantitative methods were used to analyze the representations. The team of researchers first determined which attributes were most significant by collectively reviewing a sample of the data. Codes were identified and then defined. Each researcher individually analyzed all representations using the coding system developed. This process (i.e., defining the codes and analyzing the data) was iterated a few times until the inter-rater reliability was over 90% [8]. One source of discrepancy among researchers related to the interpretation of representations in the absence of arrows. The team decided to use the convention of reading the created models from top to bottom and left to right. Table 3 shows the coding system that was used.

TABLE 3: CODING SYSTEM

Code	Explanation
Linear or Circular	Is the representation linear or circular? To be classified as circular there must be no clear start or end phase.
Start (Y/N)	Is there a clear starting point?
Starting Step	What is the starting step? This is only answered if there is a clear starting point.
End (Y/N)	Is there a clear end point?
Ending Step	What is the ending step? This is only answered if there is a clear end point.
Iteration (Y/N)	There is iteration if any step is repeated
Major or Minor Iteration	The iterations are classified as: Minor: if there is only a repeat of the steps: improve, test or create. It can also be considered minor if there is repetition of any step before create. Major: if there is repetition of either: ask, imagine, plan, or research, after the create step.
Steps Omitted	Any step that was omitted from the 5 that were given to the teachers, or the 7 that were given to the first-year students.
Steps Added	Any information that was documented on the blank cards and incorporated in the representation.

V. RESULTS AND DISCUSSION

Tables 4, 5 & 6 summarize the results of the analysis.

TABLE 4: Shape of representations and use of iterations

	Teacher-teams	Student-teams
No. of teams that produced representations	16	17
No. of circular representations	7	1
No. of linear representations	9	16
Completely linear	3	13
Linear with circular beginning	2	0
Linear with circular end	4	3
% of representations with a clear start point that begin with the Ask step	57%	75%
No. of representations with major iterations	15	11
No. of representations with minor iterations	1	5
No. of representations with no iterations	0	1

TABLE 5: No. of Representations with Missing Steps

	Terms given to all teams			Terms only given to Student- teams
	Ask	***Plan***	***Improve***	***Research***
Teacher-teams		1		
Student-Teams	1		1	11

TABLE 6: ADDITIONAL STEPS INCLUDED IN REPRESENTATIONS

Teacher-teams	Student-teams
▪ evaluate (inserted in multiple locations following create and improve) ▪ copy/cheat (inserted between ask, create and plan.) ▪ X plans, Y plans, Z plans (where X, Y and Z were the names of the teachers in the team) ▪ persevere, fail and innovate (positioned in the center of a circular representation with the provided terms)	▪ improvise (follows test, and listed as a parallel step with improve) ▪ § math (listed as the first step, followed by imagine)

Overall, the tower challenge seemed to encourage all teams (both teachers and students) to execute a process that was very close to the EDP models from either EiE or TeachEngineering. With the exception of the research step, which was only given to the students, over 90% of the teams included all of the other provided steps as shown in Table 5. In the context of the tower challenge it is understandable that many team did not complete the research step. They were only given 25 min to complete the task and there weren't many readily available resources for them use to explore how others may have approached the challenge. In the one teacher-team that included the term "copy/cheat," we believe that it represented a process that is akin to research.

More of the teacher teams showed their process using a circular representation. Most of the student teams showed a linear representation, however almost all teams included some type of iteration, even in a linear representation. There were more major iterations with the teacher teams which may indicate that as a group they were more willing to revisit the problem definition, re-generate ideas, or revise their plans, after realizing that their designs can either be improved or did not work as intended. More first-year student teams had minor iterations compared to the teacher teams (5 vs. 1). Only one student team, as shown in Table 4, had no iterations. Usually first-year students, and novice designers in general, struggle with getting fixated on an idea. Rather than explore other ways for addressing the problem, they continue to attempt to tweak their faulty approach in the hopes that it will eventually work, even if that means just barely meeting the requirements.

Another note-worthy observation is the high percentage (75%) of student teams that began their process with the ask step. One of the challenges in teaching engineering design is getting learners to appreciate the importance of spending time understanding the problem. The percentage is lower for the teacher teams only because there were only 7 teams that created a representation with a clear start point, and only 4 of these began with the ask step. However, more teacher teams overall showed representations where they repeated the ask step either before or after creating.

As shown in Table 6, some groups did include their own steps in addition to the named steps that were provided. For the teachers, the suggestion of "evaluate" is a term that is used in some versions of the engineering design process. As mentioned earlier, one teacher group used "copy/cheat" to perhaps represent research. One teacher group also expanded on the "plan" concept specifically showing that each member of the team came up with a plan, which was shared to then come up with a team plan.

VI. CONCLUSION

In future iterations of the activity, the researchers plan to have learners annotate their representations with explanations of the things they did in each step. This will give better insights about their thinking during the activity, and allow the researchers to refine their code system to draw more insightful findings.

Teachers and students enthusiastically participated in this activity as their first introduction to engineering design and their professional development workshop or introduction to engineering class, respectively. Lessons learned from this activity and analysis can be used to improve future professional development for teachers as well as instruction for first-year engineering students.

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