AC 2011-2576: PROBLEM DEFINITION IN DESIGN BY FIRST YEAR ENGINEERING STUDENTS

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Abstract

Engineering design involves insightful identification of factors influencing a system and systematic unpacking of specifications/requirements from goals. However, many engineering students are slow to articulate the major problems to be solved and the sub problems associated with achieving the main design goals and constraints. Prior research in design describes students' premature termination of solution finding to select a single idea. Then all other design decisions are constrained by this initial decision [1]. In this paper, we report how first-year engineering (FYE) students attempted to translate given design goals into sub-problems to be solved or questions to be researched. We found that, instead of decomposing the problem through further analysis and sense making, many FYE students tended to "restate" the goal, identify one major function, and then use hands on building as the central creative process. Further, students claimed they used a systematic design process, but observations of their problem solving process and teaming skills indicated a different behavior. Further investigation indicated that many FYE students could identify the superficial features from the problem statement, but they were not able to identify the implicit logical steps or deep structure of the problem.

Our current data provided the baseline of how FYE students abstract and interpret information from a design goal to generate a specific problem statement. We are interested in treatments to improve students' ability to recognize critical features of a given context and encourage taking multiple perspectives to identify alternative solutions. We are combining the use of graphical representational tools as organizational tools to support teams collaboration and we encourage opportunities to reflect and refine their design process. This research is relevant to engineering instructors/researchers who want to develop students' ability to deal with complex design challenges and efficiently decompose, analyze and translate the problem statements into meaningful functional specifications, stakeholder requirements and a plan of action.

Introduction

Developing problem solving skills is essential to engineering students and engineers. In ABET EC 2000 [2], outcome 3e states that engineering students must "have an ability to identify, formulate and solve engineering problems". Furthermore, flexible thinking and lifelong learning require engineering students to adaptively construct knowledge [3] based on information about a context presented to them. Therefore, identifying students' initial problem solving skills and fostering its development should be taken into consideration by engineering instructors. In this paper, we define a potential baseline measure of first-year engineering (FYE) students' problem-solving skills for framing, and scoping, of a problem context. We describe the novice behavior and discuss the strategies to foster and promote effective problem-solving techniques.

Many engineering instructors and researchers approach designing as a problem-solving process of an ill-defined , or complex, situation [4].They used the term *design ability* to define what a designer needs when the manage a design task [5]. Furthermore, Cross [6] describes the nature of design ability, with six attributes: *managing* goals and constraints; coping with ill-defined problems; *problem structuring*; *generating* solution concepts; *thinking by drawing*, and *intuitive reasoning*. This framework references five cognitive processes needed to make sense of a problem and organize information, to effectively produce a robust solution space for a potential design solution. The size and complexity of information can be overwhelming, but with these skills the complexity is managed and the engineering students can learn to cope with ill-defined aspects of a problem. This framework can provide guidance for future design studies, especially those focused on comparison of novice and expert design performance. Specifically, some common attributes of novice engineering students include: lack of generation of alternatives; unable to sustain information gathering; using subjective judgment to make decision; and reluctance to change after an initial design decision is made [7, 8, 9, and 10].

Among numerous descriptive studies focusing on engineering design process, open coding is usually used to describe how students approach a particular engineering task. Condoor et al. [11] used this qualitative method to report the conflict between designers' actual behavior and the prescription of how they should design. By analyzing a series of verbal protocols, Cross et al. [12] identified how second through fourth year students performed differently in terms of design. In our study, we adopted a similar qualitative method and we were interested in the very first steps of the design process. Specifically we were interested in how students comprehend the problem and define desired goals/requirements for the process. Furthermore, open coding provides a method of defining classification of actions students display during the process. Prior research in undergraduate students' design processes could provide a general framework for what to expect in students' process [13]. We attempt to now provide a lens to review individual students' response to "what problem were you trying to solve?" involved identifying "how did they formulate their problem statement". Students' responses were compared for similarities and contrasted to determine a general hierarchy of their response.

One of our primary aims is to investigate how well students translate project goals, or aims, into concrete objectives they need to achieve and the criteria they will use to achieve those goals. In our terms, this translation of goals into concrete problems to be solved is part of the problem definition process. We believe engineering students will mature in their approach to engineering problems by when they can differentiate goals/requirements and the specific problems they will need to solve to achieve those goals. Therefore, one of our goals for this study involved describing how students articulate their definition of a problem in terms of engineering goals beyond the rearticulating of the explicit goals presented by a client.   As part of this description we are further interested in what features students attune to and what they invent as a description of a problem.

The methods section provides a detailed project statement student teams completed as part of an assignment for a First Year Engineering course. The project statement mentions a specific goal of maximizing both the height of a tower, weight it can withstand and the efficiency of materials used. These constraints are further defined by a mathematical expression that implicitly defines a priority on these constraints. Our goal is to improve students ability to make these constraints more explicit as part of their problem definition process of the design task. Therefore, we are looking for students to go beyond restating the goals provided and transforming those into specific items they are trying to achieve and how they will achieve them (i.e. the actions they will take). We defined two levels of measurement for this analysis. The first is a review of student teams' executive summary of their project. In this analysis we looked for the explicit statements of the problems to be solved and the actions students identified. This definition may have emerged as either part of their initial analysis of the problem, and or as part of their reflective analysis of what they would have been done to improve their design. The second level of analysis was to observe a similar level of analysis by students individually when asked to answer the questions "What was the problem(s) you were trying to solve as part of Project 1"?"

Research questions:

1. How do FYE students comprehend and state their initial understanding of a given engineering problem?
2. How do FYE initially indentify the primary function of an engineering system (device or process) they are designing?

Methods

Participants

The participants in this study included sixty-four students enrolled in an honors version of the first year engineering (FYE) course at a large midwest university during the Fall 2010 semester. These students self-select into the course and were accepted on a first come bases. These students have a strong academic background and historically are highly motivated to achieve academically.

Instructional Plan

The following Straw Tower Project was presented to student teams in the first week of their first semester at the university. The project was primarily a team building exercise to increase the cohesiveness of the team early in the semester. The task was also designed as an initial introduction to an engineering design activity that required analyzing the design goals and identifying a critical strategy toward achieving the end goals. Eight weeks into the course we asked students to reflect on this challenge and model the critical elements of the challenge using tools they have been developing to support the design process. As instructors, we were interested in exploring how FYE students comprehend, analyze, reason about a complex engineering problem, and provide scaffolding to promote the development of adaptive expertise and knowledge transfer.

Straw Tower Project

Overview

The purpose of this project is a team building exercise. The materials your team is given include: 50, ≈ 7.75" plastic straws and 1 roll of ¾ inch scotch tape. *You may not purchase or substitute materials for those which have been provided, even if you lose, cut, destroy or otherwise mangle said materials.*

You are to build a free-standing straw support structure that maximizes both height and the amount of weight it can support while minimizing the number of straws used (i.e. less expensive to construct). The structure should be constructed in such a way as to freely support (i.e., without being held or balanced) a 4 inch by 4 inch square of corrugated cardboard (or similar material) loading platform at its apex. The 4 inch by 4inch square of corrugated cardboard will serve as the loading platform which will support a one-liter plastic loading container (or a container deemed equivalent).

Your project score during the demonstration will be calculated by:

$$Score = \frac{1}{50 - unused\ whole\ straws} weight^{(height-0.6)}$$

where the weight will be measured in ounces and height in feet.

Other Restrictions

- Minimum length of a vertical (or near vertical member) member is 3.75 inches.
- A continuous piece of tape cannot extend more than 1 inch from the end of a joint.
- Tape may not be used for structural support.
- Straw overlap may not exceed 1 inch.
- The only materials that can be used to construct your tower are the straws and tape. You are not allowed to use any other material (e.g., the paper wrappers the straws came in, the rubber band used to bundle the straws, etc.).

Demonstrations

- At the demonstration, your tower will be free-standing on a concrete (or tile) floor. You will not be allowed to tape, hold, or otherwise manually support it in place.
- The plastics loading container will be placed in the center of the 4 inch by 4 inch loading platform. Lead shot will be slowly poured into the plastic loading container until the tower fails (i.e., as determined by a member of the teaching team when he/she believes

the tower is no longer capable of carrying the weight of the lead shot filled container). Since the loading container has a finite base area, you should not assure a point loading condition.

Procedure

We asked teams to write a 1-1.5 pages executive summary after the tower demonstration. Their task was to highlight the unique features of the support structure and a factual description of the performance of the tower design. Open coding was used to evaluate the each team's report for critical features of their process. The teams' executive summaries were analyzed by means of a qualitative and inductive method in which categories of responses emerged from the data themselves [14].

Results

Level One Measurement: Team reflection

The study focused on students' abilities to recognize critical features of a given context and balance all the major constrains as a whole. Table 1 summarizes the major categories of students' responses to the question "how do you determine the primary function of a complex engineering problem in your initial evaluation?"

Table 1. Students' responses to how they determined the primary function of the straw tower.

Category One. Build the tower directly without determining the primary variable and the potential magnitude.	
S - Structural techniques T - Team discussion	S - Overall, our tower did not maximize height as much as the other variables, but this structure let us maximize the weight that it could hold, as well as minimize the straw count. T - After a team discussion, we agreed that a shorter tower with more emphasis on weight would yield the best result.
Category Two. Analyze the score formula and determine the primary influencing variable	
H - Height is more important than Weight HW - Height and Weight is equally important W - Weight is more important than Height	H – "Looking at the equation we suspected that height would be the most important factor, and by graphing a few functions with estimated values for everything except height we saw that points increased much faster with more height." HW – "Looking at the formula used to compute our score, our team decided upon making a tower which balanced height and weight, as opposed to building for either extreme." W – "Although the score is based exponentially on height, a short strong tower could score just as well as, if not

	better than, a tall weak tower if enough weight was supported. All fifty straws were used and a goal height of 1.6 feet was set so that the exponent in the score formula would be above one".
Category Three. Refine initial strategy based on reflection of initial design outcome.	
PP-Personal preference	PP - The score formula implies that height is the most important factor because it is an exponential function whereas the others are linear. By making a slightly higher tower we could have had a much higher score, however, we chose to make sure that the stability was sufficient instead of just making an extremely tall tower.

In students' executive summary, we realized almost all the students had great interest in talking about their strategies for making the tower sturdy and stable, but few of them focused on how to build the tower tall. Table Two summarized students' strategies to maximize the amount of weight the tower can support.

Table 2. Strategies to maximize the amount of weight the tower can support.

Goal One. Build a strong base.	
TB- Triangular base SB- Square base PB - Pentagonal base	TB - We used this (triangular) base rather than a rectangular base because with only three sides the base had more structural support so it was stronger. SB - The tower should have a square base, because four columns would be sturdier than three. PB - We build a structure with a pentagonal base which would be vertically reinforced by triangular support.
Goal Two. Make firm connection to avoid twisting.	
BC – Bend the straws in the center. IS – Inserted straws. AS – Angled Struts	BC - Straws were bent in the center in order to make the corners of the base sturdier. IS - One straw was inserted into the other and secured with tape in order to strengthen the connection. AS - : For every (angled) struts (joined to the vertical columns), we would make a vertical slice approximately one inch long in the vertical straw column and slide the angled struts into the slit, then reinforce with tape.
Goal Three. Distribute the weight to each beam equally.	
TTL – Tapered top layer. CC – Centered cup.	TTL - The top layer of our tower is tapered in order to distribute the mass more effectively and create a better center of balance.

	CC - We centered the cup over the straw tower so that the weight would be distributed appropriately on our structure.
Goal Four. Ensure the vertical support is sturdy.	
AB – Angled beams TS – Triangular Structure SF – Square Frame DCB - Diagonal cross braces MC – Main column	AB - Our tower also used angled vertical support beams rather than directly vertical beams. TS - In order to further support the structure, triangular structures were added in between each support level. SF - Three square frames were developed and secured to the outside of the structure. DCB - The diagonal cross braces made a big difference in preventing this (twisting). MC - A main load-bearing column that would be the core of our tower.
Goal Five. Have stable top.	
"V"S – "V" structure VS - Vertical support	VS - We kept the portion of the tower we had already built with a V structure for a bit more support near the top. VS - The bottom layer and second layer narrowed as they went up, while the top layer had completely vertical supports.

As illustrated in Table 2, FYE students had the potential to develop multiple strategies to reinforce one specific alternative. They demonstrated great practical skills to build a sturdy straw tower. They were also able to reflect on their performance and proposed great suggestions for improvement. Instead of careful planning, students' appeared to use a "trial and error" approach. As instructors, we should guide students to become more comfortable with systematic design process.

Compared to the diverse and creative strategies to maximize the held weight, few students considered the strategies to maximize the height, which was the most critical variable in the formula. Some students mentioned that they might want to save more straws to make the tower tall, and others preferred setting a goal for height before building. Interestingly, one group of students identified height was the most important factor "*because it is an exponential function whereas the others are linear*", but they still determine to build a tower that can hold more weight.

We were glad to see several students realized the importance of the formula and tried to analyze the variables before building the tower. The team who had the best performance mentioned that their team favored using straws for height rather than stability. Their tower was 35" tall and held 36.71 oz., giving a point score of 84, while a group with a shorter tower was able to hold more than twice the other teams' weight but only received 4 points. Another group who also identified the importance of height even mentioned if they had a second chance, they would build an extremely high tower with very limited bearing capability. In this case, they could still get a very high score. However, as illustrated in Table 1, many students failed to identify height as a more important variable than weight if they wanted to achieve a good result. Some of them claimed Height and Weight were equally important, and the other believed Weight was more important than Height. Their incorrect judgment directly led them to build towers that had unsound performance. As instructors, we believe students' ability to translate the problem statement into meaningful specifications would be highly improved if they could correctly comprehended and reasoned the relevant mathematical models, or some quantifiable methods, for justifying their design decisions.

Level Two Measurement: Individual Responses

Eight weeks into the semester we asked participants to individually answer the question "what was the problem(s) you had to solve for Project 1?" As illustrated in Table 3, 36 out of the 64 students simply repeated the project goal "to build a free-standing straw support structure that maximizes both height and the amount of weight it can support while minimizing the number of the straws used" (we coded as 'two max one min'). Twenty four students mentioned the details of given materials, such as quantities (we coded as 'specify the material'). Fourteen students claimed the problem to solve was to maximize the score in the formula (we coded as 'formula definition'). Three students identified height was the most important variable if they wanted to achieve the best performance (we coded as 'height most important'). Three students believed they had to balance between height and weight in order to get the maximum score (we coded as 'balance between height and weight'), and two students included detailed issues, such as taping and connection, in their problem identification (we coded as 'detailed issues').

The majority of the students couldn't distinguish "goal statement" from "problem statement", which the latter one requires students to consider "what to do next to achieve the goal". Initially, we expected students to decompose the giving information by discussing the important variables of the formula, debate potential tower characteristics, and plug in theoretical values to better understand the problem. However, many students tended to "restate" the goal, identify one major function without careful examination, and rushed to build the tower. Furthermore, as illustrated in Table 1, several students claimed that after team discussion, they agreed to build a shorter tower with more emphasis on weight. Instead of analyzing the formula, these students relied on "team agreement" to determine the building plan. Such behavior made them only capture the superficial features from the problem statement, but failed to indentify the deep logic of the problem.

Table 3. Individual responses to "what was the problem(s) you had to solve for Project 1?"

No. of Students (total: 64)	Coding Schemes	Examples
36	Two max one min	"The purpose of project 1 was to design a tower that had the greatest height and held the most mass using the least number of straws."
24	Specify the material	"We had to build a tower out of a limit of 50 straws, 1 roll of tape and with set construction guidelines."
14	Formula definition	"We wanted to build a straw tower maximizing points earned where points = $\frac{1}{50-unused\ whole\ straws} weight^{(height-0.6)}$"
3	Height most important	"Building a tower out of straws and tape that maximized first height, then weight held and efficiency."
3	Balance between height and weight	"The problem we had to solve for project one was balance between how height to make our tower verse how stable and weight accepting it was. We had to make it high, while keeping it strong."
2	Detailed issues	"We had some problems with finding an ideal taping method."

Conclusion

First year engineering honors students are very bright and have had multiple opportunities to solve problems both informally and formally before becoming an undergraduate engineering student. Design problems may be new to many students as well as a formal design process. Still, the design ideas the teams generated for the straw tower displayed good intuitions about the structural mechanics necessary to combine both height and weight. Further, as a team product, the executive summary displayed adequate descriptions of process and reflection on what they constructed. However, individual team members' analysis of the task was not as resilient several weeks after doing the activity. Students' insights about how to systematically approach the problem and analyze specific problems to be solved still require further improvement. They also need to learn what factors most influence the outcome of their design. From these results individual students are less likely to articulate the level of specificity that might be observed by an expert engineer. The results from this study provide a general baseline of how students articulate their comprehension of a problem like the straw tower design and their ability to identify and differentiate the potential influence of these factors. As systems become more sophisticated, and require additional domain knowledge, these skills will be harder and harder to develop and will require skills for defining how a system functions and how a client's needs could influence how a particular function is achieved in their design. Students need to learn how to use various tools to help them manage the complexity of a problem. That is, understanding how one factor influences other factors and how that relates to overall goals. These skills are vital to students' success and require a sequence of design experiences to accomplish it. Instructors need methods like the ones in this study to evaluate students' progress toward important design skills associated with problem comprehension, definition and scoping. This knowledge can inform the design of assessments, track students' progress and provide feedback to students on ways to help them improve.

In this course teams were given additional design challenges that required them to systematically reflect on the goals and translate them into specifications and metrics. We anticipate this kind of training enhances students' ability to approach design and we will test it in a follow on study. The same students are now enrolled in the Spring 2011 semester. The course objectives are similar, but the expectation on students' performance is increased. New teams are formed and a similar team building design activity is being explored. A pretest is being conducted to evaluate individual's approach to the design challenge prior to building or testing. Teams will need to generate similar executive summaries and analysis of the system. We anticipate that more students will demonstrate an ability to identify and articulate various sub-problems to be solved as part of the design challenge. This will indicate important trajectories of student learning about design that will transfer to future design challenges.

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