AC 2011-277: MOVING BEYOND FORMULAS AND FIXATIONS: EXPLORING APPROACHES TO SOLVING OPEN-ENDED ENGINEERING PROBLEMS

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Moving beyond formulas and fixations: Exploring approaches to solving open-ended engineering problems

Abstract

Open-ended problem solving is a skill that is central to engineering practice. As a consequence developing skills in solving such problems is imperative for engineering graduates. Open-ended problems are ill-defined and can have more than one viable solution. Solving open-ended problems therefore requires consideration of a complex array of constraints and the paths to a solution are many. The qualitative study presented in this paper explores the approaches taken by eight materials science students to solving an open-ended problem. A think aloud method was used to collect data and analyze the problem solving approaches of each student. Each student described their actions and thought processes aloud as they worked through the problem and these think aloud sessions were video recorded and transcribed for analysis. In addition, each participant's final written solution was graded for quality.

Among the eight participants a spectrum of solution paths and problem-solving processes was apparent. Through the use of script analysis, three approaches to solving the problem were identified (extreme fixation/overwhelmed, fixated and uncertain, and systematic and linear). The participants with the lowest solution scores had difficulty making important decisions due to extreme fixation on a single task, whereas the participants with the highest scores took very systematic and linear approaches to the problem, avoided fixations on irrelevant concepts or re-conceptualizations, and were able to identify critical decision points in the problem solving process. Results suggest that performance on open-ended problems is related to the processes students use. Thus, careful attention must be paid to the way in which open-ended problem solving is taught.

Introduction

Open-ended problem solving is a skill that is central to engineering practice and one that engineering students are required to develop. ABET (2009) criterion 3c states that students must develop "an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability."(p. 3) Open-ended problems are by nature ill-structured to varying degrees. Such problems lack definition in some respect and as a result problem constraints may be unclear, vaguely defined, or missing altogether (Jonassen, 2000; Simon, 1973). In addition, multiple criteria may exist for evaluating solutions to such problems. Because of their ill-structured nature, open-ended problems may have multiple solutions and the paths to those solutions may be many (Jonassen, 2000). Ill-structured problems require the problem solver to develop constraints and make personal judgments about the problem. The nature of open-ended problems can therefore result in discomfort and frustration for those who are accustomed to solving well-structured problems with clear constraints and only a single solution.

Solving open-ended problems requires a different set of skills and cognitive processes than those required of closed-ended problems (Schraw, Dunkle, & Bendixen, 1995). Skills unique to successfully solving open-ended problems involve not only the correct recall of information but also an appropriate application of the information to a problem in which the correct use of the information is not clearly defined. Jonassen and Hung (2008) argue that the ability to solve well-structured problems in the classroom does not necessarily lead to the ability to solve ill-structured problems in the workplace. Sheppard et al. (2008) also warn that:

> *Solving right-answer problems is not necessarily problem solving: the problems that students are typically asked to solve do not build up the kind of problem-solving skills they will need later in their program or in practice. They do not lead to the habits of mind that, whether the students become engineers or not, are such valuable contributors to work and citizenship.* (p. 48)

Engineering educators have recognized the importance of developing open-ended problem solving skills and efforts to integrate open-ended problem solving experiences across the engineering curriculum are not new (Incropera & Fox, 1996; Mourtos, Okamoto, & Rhee, 2004; Woods et al., 1997). Woods (2000) notes that the literature is full of problem solving strategies, but that few have been supported by research evidence. Several studies of engineering design have found that experienced designers spend more time in problem scoping than novices (Atman et al., 2007), and that they also make more frequent transitions between various design activities such as defining the problem, gathering information, and generating ideas (Adams, Turns, & Atman, 2003). Most of the work in engineering problem-solving has focused on the technical steps associated with problem-solving (e.g. defining the problem, gathering information, etc.) What is less developed in the literature is an understanding of the cognitive and psychological processes involved in engineering problem-solving.

The study presented in this paper explores the approaches taken by eight materials science students to solving an open-ended engineering problem. The research question guiding this study was:

> What factors contribute to undergraduate engineering students' ability to solve open-ended engineering problems?

This work is part of a multi-year mixed methods study of open-ended problem solving. The findings presented here represent the qualitative portion of the study and are drawn from data collected during the Spring semester of 2010. A think aloud method was used to collect data on eight participants as they solved an open-ended problem. During individual sessions, each participant was asked to describe their actions and thought processes aloud as they worked through the problem. These think aloud sessions were video recorded and later transcribed for analysis. The problem is presented below.

Bridge problem:

A truss bridge requires 40 members, each of which is 12 feet long and experiences its maximum load when in tension. The bridge is designed so that the maximum load experienced by each member is 60 MN. You are bidding on the contract to provide these 40 members. Provide a recommendation as to the design specifications and cost for the job.

To provide a measure of the quality of each student's solution the following rubric was used to evaluate the students' written solutions. The scores for each participant are reported later in the paper.

Scoring rubric

1. Considered more than one type of material	2 pts.
2. Selected a cross-sectional shape and size	2 pts.
3. Calculated stress in members	2 pts.
4. Compared stress in members to yield stress	2 pts.
5. Found volume of member selected	2 pts.
6. Calculated total cost of job	2 pts.
TOTAL	12 pts.

Research Approach and Method

This study is guided by a constructivist theoretical perspective. This perspective posits that individuals construct knowledge through interactions with their environment and that human perceptions, understandings, and realities are based on the lived experiences of individuals (Cardellini, 2006; Crotty, 1998; Gordon, 2009; Kincheloe, 2005). Individuals create, interpret, and recognize knowledge in diverse and contextual ways (Windschitl, 2002). An individual is seen as an active knower and as a consequence personal reflections on experiences are integral to the data collection process (Crotty, 1998; Fosnot, 2005; Schwandt, 2001). In the context of the think aloud method discussed in this paper, students generated knowledge about their problem solving strategies and approaches by reflecting actively and in real-time on their thought processes and meaning making while solving the given engineering problem.

The think aloud method used to collect data for this study involved asking participants to verbalize their thoughts while conducting a specific task (van Someren, Barnard, & Sandberg, 1994). This method was developed in the cognitive psychology field and is viewed as a means of gaining insight into mental operations from which conjectures can be made about the cognitive processing of participants (Ericsson & Simon, 1993; Johnson, 1993; van Someren et al., 1994). During the think aloud process participants are encouraged to constantly talk aloud, describing all their thoughts, regardless of how inconsequential they may think their thoughts are to the problem solving process. As Ericsson and Simon (1993) suggest, participants should verbalize everything that passes through their minds as they search for solutions to the problems they are working on.

The think aloud sessions were conducted individually. Each session began with one of the researchers explaining the purpose of the study and describing the think aloud method as well as the role of the researcher in the process – to prompt participants to continue talking out loud if they fall silent. At the start of the think aloud sessions, participants were provided with the problem statement on a single sheet of paper, a pad of paper on which to work out their solution, a calculator, and a copy of an introductory materials engineering textbook for use as a reference (Callister, 2007). The participants' verbalizations and actions were captured using two video cameras. One camera was placed in front of the participant and the other was positioned directly over the shoulder of the participant to provide a view of the materials on which they were working.

Population and Participants

Eight senior undergraduate materials engineering students from a large southeastern university participated in this study. Participants were recruited from a pool of 60 seniors. Seniors were recruited because of their academic experience and consequent level of content knowledge in the subject area. Approval from the university's Institutional Review Board was received prior to commencing data collection. The first eight students to express interest in participation were selected for this study. As will be seen in the Findings, the range of responses received suggests that there was no self-selection bias. The names for participants used in this paper are pseudonyms.

Data Analysis

The analysis was guided by a semantic script analysis (Fonteyn, Kuipers, & Grobe, 1993; Funkesson, Anbäcken, & Ek, 2007). Script analysis was conducted to clarify the ambiguity of participants' reasoning processes through a description of their problem solving experiences. Fonteyn et al., (1993) argue that script analysis allows for the investigation of the types of information that participants attend to while problem solving in terms of a) their method of structuring the problem, b) justifications of the decisions they make, and c) their problem solving plan.

The recordings of the think-aloud activity were transcribed verbatim and the transcripts were treated as the data for the analysis process. The analysis involved three steps: 1) a referring phrase analysis, 2) a script analysis, and 3) an assertion analysis. The first stage, or referring analysis stage, was used to identify noun, or noun phrases, associated with decision points in the think-aloud process. The script analysis portion of the analysis involved categorizing the descriptions of participants' actions at associated decision points during their think-aloud sessions. This included actions such as 'conceptualizing the problem', 'accessing the book', 'self-evaluation' and 'calculating'. The final step of analysis was an assertion analysis which involved identifying different types of assertions used during the problem solving process. Five different assertion categories were used: 1) Connotative assertions – consideration of different alternatives or comparisons of concepts, 2) Indicative assertions – considerations of future actions or intentions during the problem solving process, 3) Interrogatives – questions asked during the process, 4) Causal assertions – reflections on relationships or connections between concepts and ideas, and 5) Declaratives – clear definitive actions or decisions articulated during the problem solving process. The table below provides an example of a script analysis worksheet generated by the researchers.

Table 1. Example of a script analysis worksheet

Data excerpts	**Referring phrase analysis**	**Script analysis**	**Assertion analysis**
So first thing I'm writing down the given. You have 40 members. Each are 12 feet long and maximum in tension.	members tension	Rationalizing approach, Studying problem	Declarative
So all we're doing is just it's 12 feet long and this building needs 40 of them. Cost for the job would be hard to do without the current prices of what the material would be.	Prices material	Studying problem	Connotative
My plan is just to solve one and to kind of come up with those specifications. But as far as the cost for the job part, I'm not sure I can actually do it without like the current price of what the materials would be.	specifications cost price materials	Rationalizing approach	Indicative

Two researchers were involved in the analysis process. Both researchers crosschecked the first two transcripts analyzed by the other to ensure that there was consistency in their application of the three stages of analysis. After completion of all three levels of analysis, connections were sought across all three in an effort to determine linkages and diversions in the data as representative of the students' problem-solving experiences. In analyzing across participants, patterns were investigated by comparing their referral, script, and assertion analysis patterns with their associated scores for the problem as determined by application of the grading rubric to participants' solutions. A third researcher prepared process diagrams of the solution paths for each participant based on the decisions and actions that participants took during the problem solving process. In these diagrams, oval objects represent decisions while rectangular objects represent actions taken.

Findings

Participants displayed various approaches to solving the given problem, of which some resulted in a viable solution while others did not. The participants, their problem solving approaches and solution scores are presented in Figure 1. In our data set, the two participants with the lowest solution scores, Joshua and Matthew, demonstrated difficulty making important decisions because of extreme fixations. Joshua spent all of his time trying to decide what material he should specify for the bridge while Matthew made a valiant, but ultimately unsuccessful, attempt to develop a single unified mathematical expression that he could use to solve the problem. Jessica, Amanda, and Justin also exhibited fixations of various kinds, but achieved higher scores due to their ability to set up the problem correctly and resolve some critical problem solving decisions. These three participants also exhibited high levels of uncertainty during the problem solving process. The three participants with the highest scores, Michael, Christopher, and Ashley, all followed very systematic and linear approaches to the problem. They avoided fixations and distractions and were able to identify critical decision points in the problem solving process.

The problem solving approaches of the participants in this study have been grouped into the following three categories:

1. Extreme fixation/overwhelmed
2. Fixated and uncertain
3. Systematic and linear

In the following sections we discuss these three categories of approaches as well as the relationships between the approaches taken by each participant and the quality of their solutions.

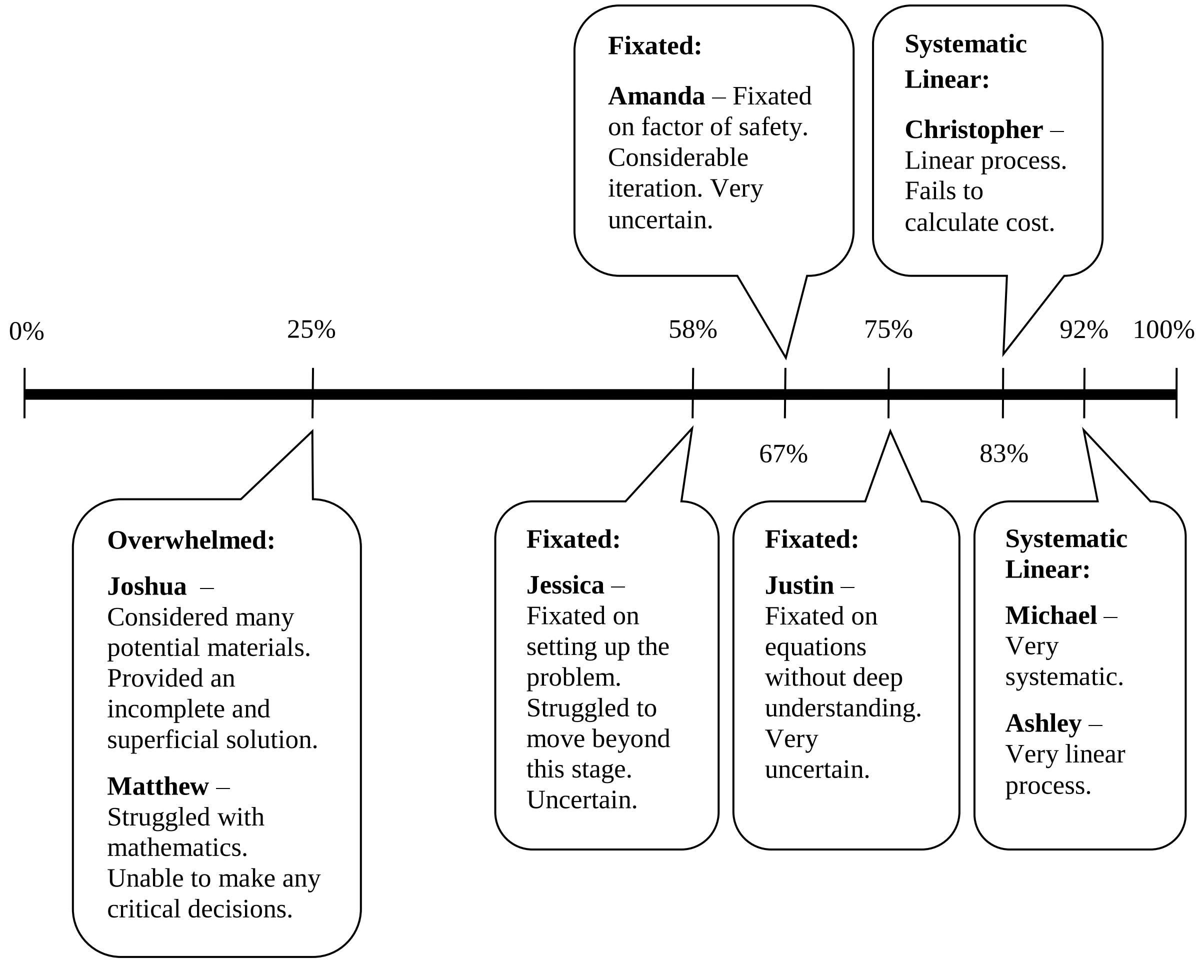

Figure 1. Participants' problem solving approaches and solution scores

1. Extreme fixation/overwhelmed

Both Joshua and Matthew faced major obstacles when trying to make forward progress in the problem solving process. Both became quickly fixated on a single problem solving task and were never able to provide a complete solution to the problem. Joshua spent all of his time considering various materials that he could specify for the bridge members. For example, he stated:

> *Now I'm trying to decide. I'm looking at all these different – they give you a lot of information with different kinds of steel which means I can be kind of specific when I'm picking something. So right now I'm thinking stainless steel would be great because it would degrade less but that wouldn't be very good because it would be expensive… You're not going to need that much strength so you could probably use a pretty low alloy steel.*

Joshua also appeared to be overwhelmed by the open-ended nature of the problem. For example, while examining the properties of materials in the appendices of the textbook he exclaimed, “Oh man, all this stuff! Titanium would work but that would be ridiculous for a bridge. You don’t want any of those (glancing at other choices). No, no, no, no.” It can be seen from the illustration of his solution path that Joshua was stuck in a materials selection loop (see Figure 2), spending all of his time contemplating various materials. After selecting a material, Joshua dismissed or overlooked the other requirements of the problem, failing to specify dimensions for the bridge members as well as calculate a total cost for the job. Joshua spent significantly less time on this problem compared to the other participants and ended his solution very quickly and suddenly.

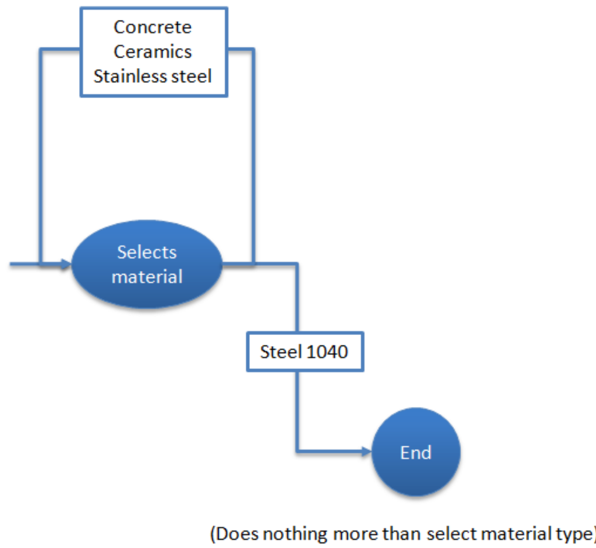

Figure 2. Solution path for Joshua

Matthew also became fixated at the start of the problem solving process and, like Joshua, was never able to progress to a solution. He spent all of his time attempting to develop a single unified mathematical expression that he could apply to solving the problem, struggling to create an expression that would relate mass, density, applied force, and cost values. Because of this early fixation, his solution path is very simple (see Figure 3). After struggling for quite some time to develop an all-encompassing mathematical expression, Matthew’s frustration became evident as he exclaimed:

> *That doesn’t seem to be working! So let’s see, all of these are in stresses. Um, I can compare the stress to the density, but I also have the price. Basically I need to find density as mass times volume. Volume, where is this? And volume is here. So um, let’s see. I’ve got the … I’m completely blanking out here right now.*

Matthew did not appear to recognize that the problem was not fully constrained and his fixation on algebraic manipulations distracted him from decisions that he needed to make to progress toward a solution. He never arrived at the point of considering properties of specific materials because he did not feel that his mathematical expression was complete.

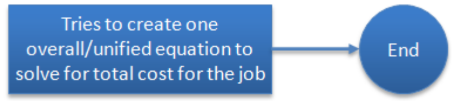

Figure 3. Solution path for Matthew

Both Joshua and Matthew made many causal and declarative statements which would seem to indicate a high level of certainty about their problem solving approaches and answers. However, this certitude masks deficiencies in the approaches of these two students. For example, Joshua very confidently talked himself out of providing cross-sectional dimensions for the bridge members explaining:

> *MN [Meganewtons] is force over area which means they already have an area, which means they already know the cross-section shape that they want these to be. So they really don't care about me deciding what shape they should be, so that's not what specification means.*

After confidently deciding to ignore cross-sectional dimensions, Joshua then focused solely on selecting a material for the bridge members, explaining:

> *It's got to be cheap, so either some kind of concrete, or like steel, is what bridges are made out of and it's tension, so you really don't want ceramics because ceramics suck at tension. So metals are the way to go here. Steel's a good cheap metal.*

Therefore, instead of providing a total cost for the materials, Joshua only used cost as a superficial criterion in the material's selection process.

If Matthew's declarative and causal statements are observed in isolation they too appear to represent strong assertions. However, when viewed collectively they reveal a high level of confusion and uncertainty. For example, after reading the problem statement, Matthew struggled with whether he should include density in his calculations:

> *There's no mass limitation so I don't think density comes into this. Um, tensile strength isn't stress. We don't have any modulus because again there's no size. I guess we could put a density term in, well, no, because there's no mass. Mass would be related to the cost. So let's see. In order to relate the area, we take the area; we want to convert this into a density which will then convert to a cost.*

2. Fixated and uncertain

Jessica, Amanda, and Justin were also less successful in solving the given problem because of premature fixations on irrelevant factors which took attention away from critical decisions that needed to be made to move forward with the problem. These three participants also exhibited higher levels of uncertainty than the other participants in this study. However, these participants received higher scores for their solutions than the previous two participants because they were able to set up the problem correctly. Jessica, for example, selected arbitrary cross-sectional dimensions for the bridge members, calculated an applied stress for the members, then applied a safety factor and started looking for materials that could handle the applied stress. This burst of progress got her close to a solution, but occurred only after a prolonged period of uncertainty while she struggled to set up the problem. Throughout almost the entire problem solving session Jessica was plagued by uncertainty and sought to rationalize each step of her problem solving approach. This is illustrated by the following quote:

> *I guess there's not enough information I would say to answer this problem… Any recommendation I would provide for the specification would be just kind of picking one and then from there kind of tailoring it to the material. And even after you get the materials just picking an area for the length and width… so it would all be assumptions. And as for the cost, it would be hard to calculate the cost because you're not given the cost of the material per, I guess, density or whatever. And you're also not given the cost of manufacturing, or the cost to even… I don't know if it's the cost to build the bridge or just the cost for the, I guess, for each member. So it's like a lot of unknowns.*

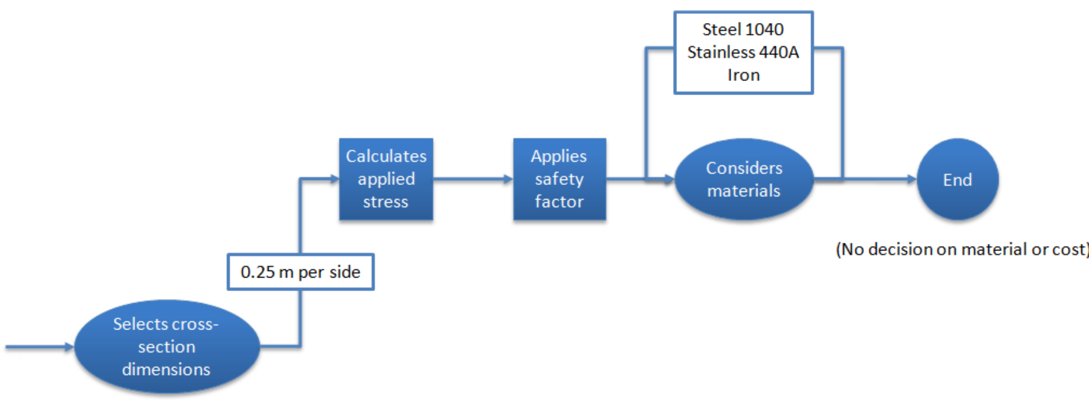

Figure 4. Solution path for Jessica

Jessica's fixation on setting up the problem and hesitation resulting from uncertainty inhibited her from simply trying out some of the problem solving steps that she was considering. She was ultimately unable to produce a complete solution to the problem.

Amanda, in turn, considered more alternatives than the other participants and also exhibited more iteration between problem solving tasks compared to the others. This is illustrated by the complexity of her solution path as shown in Figure 5. Although the iteration helped her find errors in assumptions and calculations this behavior seemed to be driven primarily by a high level of uncertainty. Often Amanda seemed overwhelmed by the decisions she was trying to make, declaring at one point:

> *I have a lot of options, so kind of since it is providing like a recommendation you would want more than one option. So, I'm debating well, do I want to do like, because there's a hot rolled versus cold drawn, or is that really that big of a deal? And, how many different options should we [be] giving them?*

Amanda also exhibited a fixation on incorporating a factor of safety into her solution even though one was not required by the problem statement. This fixation on a factor of safety carried through the entire problem. The following quote illustrates how Amanda was grappling with this self-imposed criterion:

> *Like I could just keep raising my factor of safety – just to kind of cut out materials – but then at the same time it's just always costing. You don't really want to do that. So that's another kind of thing I'm, since the factor of safety wasn't limited, or it wasn't saying oh, you should probably do it around here, that's kind of finding like typical factors of safety. So I need myself to feel a little more confident in my recommendation so… (flipping pages in the book) because I can't remember what was constituted as like a really big deal. Obviously if a bridge fails it's a pretty big deal, but I don't remember what number is… let's look for that.*

Justin's data exemplifies an approach to the problem which was driven by a fixation on formulas and equations. After receiving the problem statement Justin declared, "Guess I'll try and find equations first and then the material." Justin subsequently spent much of his time plugging values into various formulas. Although Justin was able to successfully identify important variables and formulas needed to solve the problem, he displayed a lack of depth in understanding and, like Jessica and Amanda, was plagued by uncertainty as illustrated by the following quote:

> *The answers just don't make any sense, so I'm thinking [I] probably messed up somewhere, but trying to get an answer that sounds a little bit better. So where it's going wrong in what I'm currently doing is that, that the tensile stress is so much higher than the force that it is creating – a very small width which is creating a very, like a very large volume, or I guess it's well… it's creating a smaller volume. But I want like, I'm not sure.*

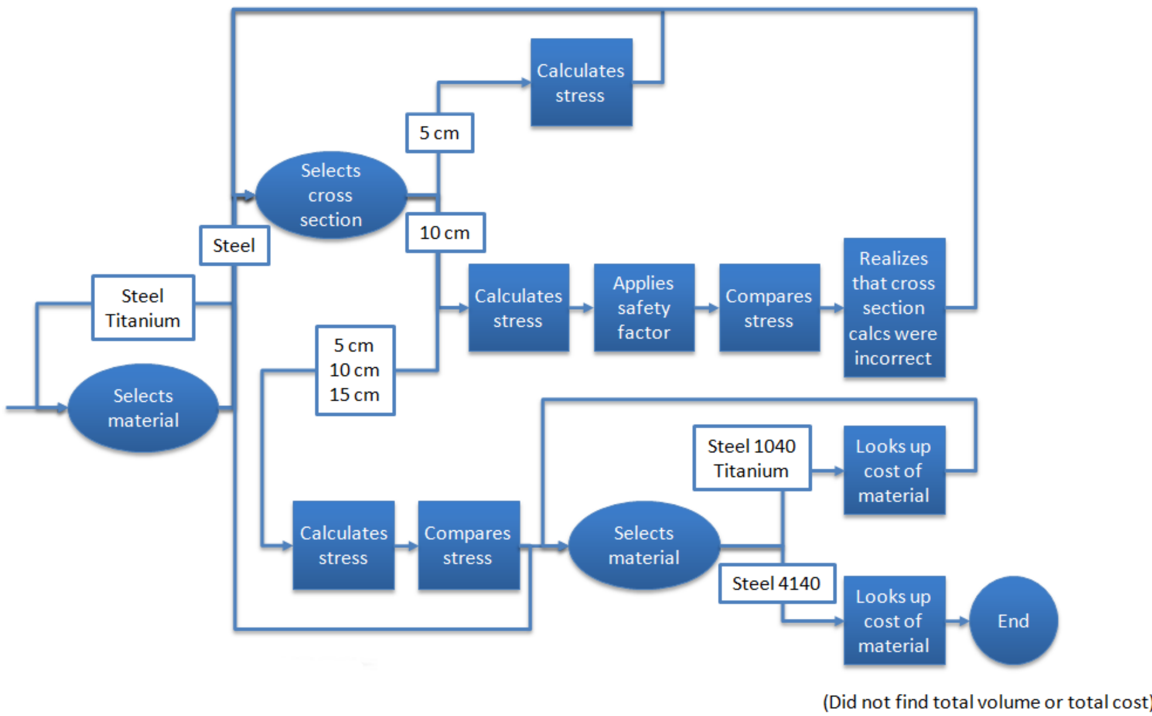

Figure 5. Solution path for Amanda

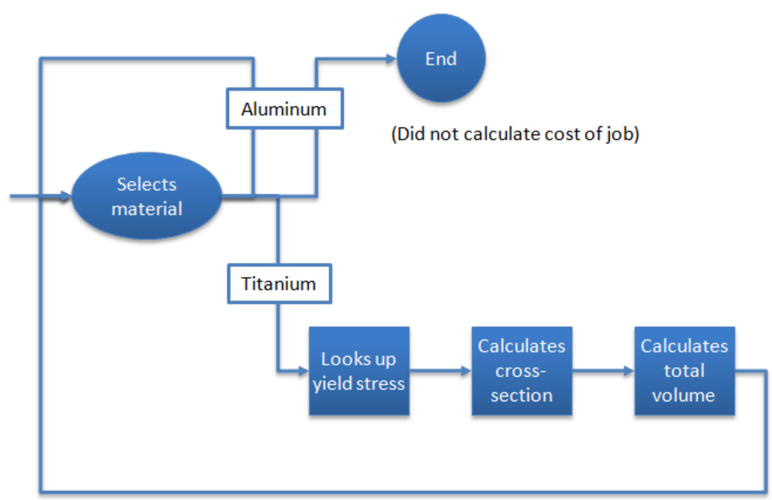

Figure 6. Solution path for Justin

After obtaining values from his calculations, doubt would surface and Justin would repeat his calculations. Justin was unable to find assurance that his solution was reasonable. Because of a fixation on trying various numbers in his calculations for the dimensions of the bridge members, Justin forgot to provide a cost for the bridge as specified by the problem statement.

3. Systematic and linear

Christopher, Michael, and Ashley's think-aloud data reveal very linear and systemic approaches to the problem (see the three process diagrams in Figures 7 - 9). Of the three, Michael was the only participant who considered a variety of possible materials that he could specify for the bridge. The other two participants quickly selected a material for the bridge and moved on to calculating dimensions for the bridge members. Although Christopher began the problem by selecting 1020 steel, he was unable to find cost values for this steel and so he selected another type of steel simply because cost values were easily found in the appendix of the provided textbook. Michael, in contrast, calculated figure-of-merit values for a number of different materials based on criteria of cost, strength, and density. He arranged these values in a table to help him select a material which represented the most advantageous combination of these criteria.

During the think-aloud sessions these three participants began many of their phrases with the word, "So,…" These declarative statements sounded very matter-of-fact and purposeful as if to say, "Here is what I am going to do…" As a result, these participants sounded very confident in their approaches as they worked step-by-step through the problem. These statements seem to indicate that they had a clear plan for the problem in mind. Each of these three participants spent less time on the problem compared to the others (with the exception of Joshua, who only gave the problem a superficial treatment and never moved beyond material selection). The linear and deterministic approaches of Christopher, Michael, and Ashley were evident in the use of many causal and declarative statements. For example, at one point Ashley explained:

> *So now I'm thinking if I should include a factor of safety for things like bridges so they're not running at exactly their maximum load. So you do that by dividing max strength [by] let's say 5. So we'll do a factor of safety of 5. And so now that gives us an area of 0.6122 meters squared. And so now each side so 0.7824 meters. Okay, so that would be the size required based on this material, and so now the cost.*

Ashley completes one task and moves on to the next in a systematic way. It is almost as if she is following a checklist. A similar purposefulness is also illustrated by a quote from Michael. After reading the problem statement Michael stated:

> *Okay. So we'll also want to have cost as a factor. Okay. So cost is going to equal the whole volume times the density times the cost per kilogram, or the cost by mass. Want to minimize the mass. So we want a high strength material, but also it has to be low cost. We can do that with a figure of merit calculation. Let's see. The volume is going to be the area times…*

Although Christopher exhibited uncertainty at times, it was clear that he was also acting purposefully as illustrated by the following quote:

I don't really know how to do cost, is the thing, because that would be entirely dependent on what alloy you're using and what processing technique and how quickly you've got to do them.

Although Christopher claimed not know how to find the cost, he was still able to identify factors that are important to developing a cost estimate. After thinking about these factors for a while Christopher was able to move forward, explaining:

Okay. So then cost. You would have to find the dollars per kilogram of steel… Forty bars times the volume of one bar divided by the density. That gives you the total mass of steel which then you multiply by cost and it gives you the cost of the raw product, or the raw material.

All three students in this category spent a considerable portion of their time doing calculations. However, unlike the other participants, they did not engage in calculations without a clear idea of how the calculations would help them to move forward in the problem. For instance, Michael explained how he was going to determine cost before engaging in actual calculations explaining, "So we'll also want to have cost as a factor. Okay. So cost is going to equal the whole volume times the density times the cost per kilogram."

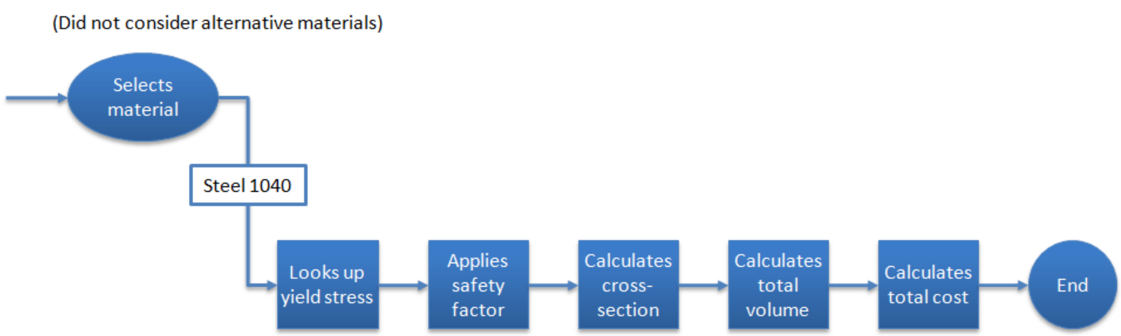

Figure 7. Solution path for Ashley

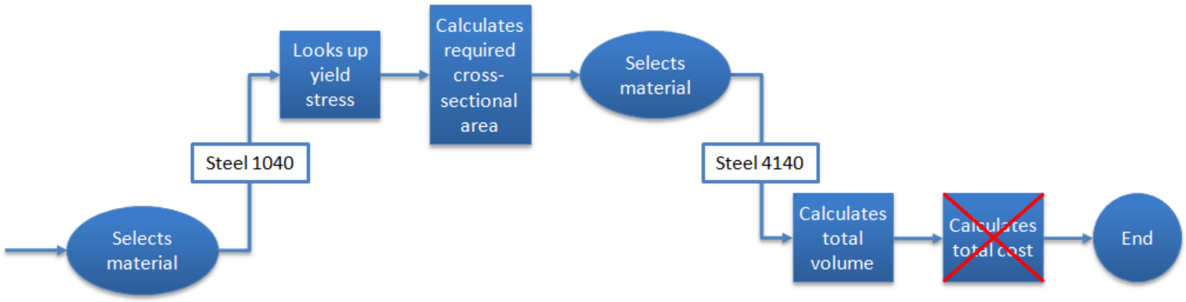

Figure 8. Solution path for Christopher

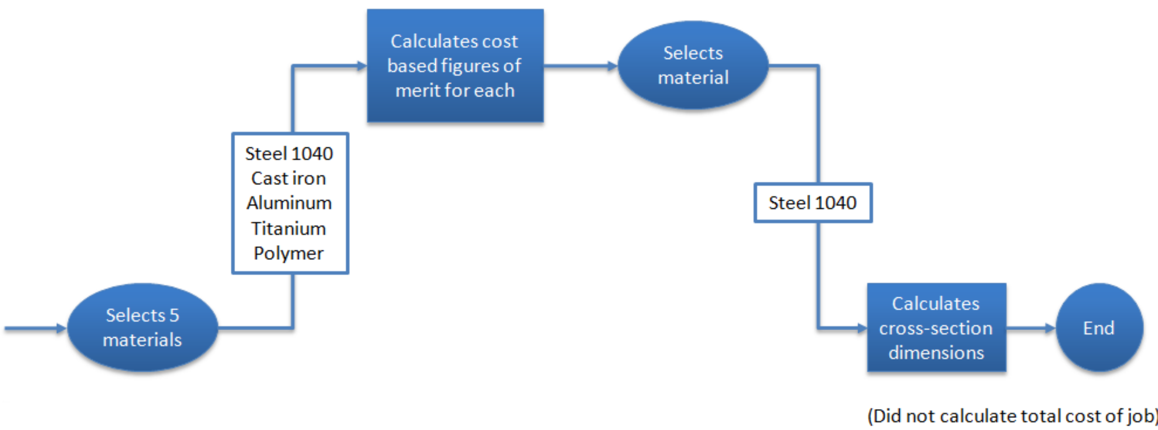

Figure 9. Solution path for Michael

Discussion

Results from this study suggest that performance in solving open-ended problems is related to the approaches that students take to solving such problems. The first category of participants in this study exhibited extreme fixations which inhibited them from addressing all of the necessary elements of the problem. The strong causal and declarative statements made by these participants suggest that they had chosen (either consciously or unconsciously) to overlook critical elements of the problem. Joshua reduced the problem to one of arbitrary material selection and Matthew attempted to reduce the problem to an algebraic exercise. Matthew's efforts were ultimately unsuccessful because he failed to recognize the open-ended nature of the problem and consequent lack of complete problem constraints. The lowest performing participants in our study may have been struggling with lack of content knowledge or conceptual misunderstandings. Nevertheless, these participants appeared to lack awareness of the deficiencies in their approaches. An obvious commonality between students who scored poorly was their focus upon inappropriate aspects of the problem. In cognitive psychology, this phenomenon is described as fixation and is associated with an increased likelihood of failure (Dominowski, 1986). Evidence for fixation behavior has also been documented in engineering design (Jansson & Smith, 1991).

Solving open-ended problems requires the ability to identify and make critical problem solving decisions (Dym, Agogino, Eris, Frey, & Leifer, 2005). The decision making process is complicated by the nature of open-ended problems; there are multiple possible solutions and multiple paths to a solution. In the case of the problem used in this study, participants could select a material type for the bridge members and use that as a constraint for determining dimensions for the members, or they could select dimensions for the bridge members and then find a material that would be able to handle the load given in the problem statement. The cost constraint given in the problem statement added to the complexity of the decision making processes. The most successful problem solvers in this study moved through the problem in a very systematic step-by-step progression. They appeared to have experiences, existing mental models, or strategies that they were drawing on to help them work through the problem.

The ill-defined nature of open-ended problems means that some constraints must be developed by the problem solver (Jonassen, 1997). The problem used in this study required participants to balance dimensional and loading constraints given by the problem statement with other undefined constraints such as material properties and cost. The problem statement did not limit participants to these constraints, however; participants were given the freedom to add more. Two participants, for example, chose to incorporate a factor of safety. However, this self-imposed constraint proved to be a distraction, particularly for Amanda. In addition, several of the participants in this study struggled to assess the quality of the solutions that they were putting forward. This evaluative component was particularly troubling for these participants because the criteria for judging their solutions were not fully defined in the problem statement. As a result, these participants exhibited a high level of uncertainty in their problem solving approaches.

The difficulty some participants had with the open-ended nature of the problem may also reflect differing epistemological views on the nature of knowledge. Stage models of development describe the epistemological beliefs of individuals. One such model is the Reflective Judgment model (King & Kitchener, 1994), which defines three major stages of epistemological development: pre-reflective, quasi-reflective, and reflective. At the pre-reflective stage individuals “do not differentiate between well- and ill-structured problems,” but view all problems “as though they were defined with a high degree of certainty and completeness.” (p. 16) Quasi-reflective thinkers “acknowledge differences between well- and ill-structured problems…they are often at a loss when asked to solve ill-structured problems because they don’t know how to deal with the inherent ambiguity of such problems.” In contrast, reflective thinkers recognize that judgments can be made based on evaluation and interpretation of available evidence. From these descriptions, we can hypothesize that students at the pre-reflective and quasi-reflective stages will have more difficulty with open-ended problems because they see knowledge as being certain and do not recognize or understand how to deal with ambiguity. Our study is being extended to measure the epistemological beliefs of students and compare that to their ability to solve problems.

Conclusions

Participants in this study were grouped into three categories based on their approaches to solving the given open-ended problem. Participants in the first group were overwhelmed by the open-ended nature of the problem as evidenced by extreme fixations on a single task or element of the problem. These participants made little progress toward a solution becoming quickly derailed by their fixations. Joshua got stuck in a materials selection loop while Matthew embarked on an unsuccessful quest to develop a grand unifying equation that he could use to solve the problem. The fixation on a single task inhibited these participants from addressing other elements of the problem.

Participants in the second category also exhibited fixations, although to a lesser degree. Jessica constantly second-guessed her work, Amanda complicated the problem with a fixation on incorporating a factor of safety, and Justin focused on finding equations into which he could plug numbers without demonstrating an in-depth understanding of the problem. Although participants in this category were able to proceed further toward a solution than participants in the first category, they struggled with much more uncertainty. The lack of constraints provided by the problem statement was particularly disconcerting for these participants. In addition, these participants were unable to effectively evaluate their solutions and thereby develop a level of certainty about their approaches to the problem.

The participants with the highest solution scores exhibited very systematic and linear approaches to the problem. These participants were able to avoid fixations on irrelevant concepts or re-conceptualizations and were able to identify the critical decision points in the problem solving process. The causal and declarative statements made by these participants display a level of confidence not found in the other participants. In addition, these participants moved confidently from one problem solving step to another as if following a predetermined plan.

Several educational questions and implications arise from this study. How can educators help students to develop successful approaches and strategies for solving open-ended problems? How can students be helped to overcome fixations? Students must be able to identify and make critical problem solving decisions, develop problem constraints, and develop criteria for evaluating potential solutions when solving open-ended problems. Jonassen and Hung (2008) suggest that a problem's difficulty must be matched to a learner's readiness. Several participants in this study did not appear to be prepared for the open-ended problem that they were facing (perhaps exhibiting low-level epistemic beliefs). Such students may need to be *gradually* weaned off the many closed-ended problems that they encounter on homework sets and exams. Diefes-

Dux et al. (2004) and Hamilton et al. (2008) promote the use of “model-eliciting activities” – problem solving exercises that require students to focus reflectively on the process of solving open-ended problems rather than on the product alone. Such practice may help students move to higher levels of epistemological development and give them greater comfort in dealing with the ambiguities of open-ended problems.

The findings in this paper are the first in a multi-year study of open-ended problem solving. Follow-up interviews were conducted with the participants presented in this paper. Findings from these interviews will help to further explain the problem solving approaches taken by the participants in this study.

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