European Journal of Engineering Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ceee20

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

Elliot P. Douglas [a], Mirka Koro-Ljungberg [b], Nathan J. McNeill [a b], Zaria T. Malcolm [b] & David J. Therriault [b]

[a] Department of Materials Science and Engineering, University of Florida, Gainesville, FL, USA

[b] School of Human Development & Organizational Studies in Education, University of Florida, Gainesville, FL, USA

Version of record first published: 28 Nov 2012.

To cite this article: Elliot P. Douglas, Mirka Koro-Ljungberg, Nathan J. McNeill, Zaria T. Malcolm & David J. Therriault (2012): Moving beyond formulas and fixations: solving open-ended engineering problems, European Journal of Engineering Education, 37:6, 627-651

To link to this article: http://dx.doi.org/10.1080/03043797.2012.738358

European Journal of Engineering Education
Vol. 37, No. 6, December 2012, 627–651

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

Elliot P. Douglas[a]*, Mirka Koro-Ljungberg[b], Nathan J. McNeill[a,b], Zaria T. Malcolm[b] and David J. Therriault[b]

[a]*Department of Materials Science and Engineering, University of Florida, Gainesville, FL, USA;* [b]*School of Human Development & Organizational Studies in Education, University of Florida, Gainesville, FL, USA*

(*Received 25 January 2012; final version received 5 October 2012*)

Open-ended problem solving is a central skill in engineering practice; consequently, it is imperative for engineering students to develop expertise in solving these types of problems. The complexity of open-ended problems requires a unique set of skills. The purpose of this qualitative study was to investigate the approaches used by engineering students when solving an open-ended engineering problem. A think-aloud method was used to collect data about the problem-solving approaches of eight materials engineering students. Through the use of script analysis three approaches to solving the problem were identified, which were consistent with the Reflective Judgment Model of epistemic development. Students who used a linear, systematic approach were most successful at solving the problem. Less successful students were overwhelmed by its open-endedness and/or became fixated on a single aspect of the problem. These results point to a need to develop open-ended problem-solving skills throughout the engineering curriculum.

Keywords: engineering education research; problem-solving; think-aloud protocol; epistemology

1. Introduction

Open-ended problem solving is a skill that is central to engineering practice and, as a consequence, it is imperative for engineering students to develop skills for solving such problems (Denayer *et al.* 2003, Winkelman 2009). Mourtos *et al.* (2004) argue that: 'Engineers by definition are problem solvers. Whether they are involved in analytical, experimental, computational or design work, engineers solve problems. Yet, real world problems tend to be quite different from most exercises found in engineering texts'. Similarly, Simon (1981) argues that design 'is the core of all professional training' (p. 129) and that: 'It has been the task of engineering schools to teach about artificial things: how to make artifacts that have desired properties and how to design' (p. 129).

Real-world design problems are generally open-ended and ill-defined, lacking complete information about problem constraints. Consequently, the problem solver must develop and contend with a complex array of possible strategies through the problem space. Problems that are missing

*Corresponding author. Email: edoug@mse.ufl.edu

ISSN 0304-3797 print/ISSN 1469-5898 online

http://dx.doi.org/10.1080/03043797.2012.738358
http://www.tandfonline.com

data or constraints are often subject to interpretation; thus, introducing a subjective, or qualitative, element to such problems. The ill-defined nature of open-ended problems can result in uncertainty and discomfort for those who are accustomed to solving problems with a sufficient level of constraints and only one correct solution. In addition to having multiple viable solutions, the paths to a given solution can be many, adding an additional layer of complexity to open-ended problems. These factors can increase the complexity of such problems and may require different skills than those required to solve closed-ended problems.

Students graduating from accredited engineering programmes in Europe, North America and elsewhere are expected to develop the knowledge and skills to solve complex open-ended design problems. European Network for Accreditation of Engineering Education (2008) accreditation criteria state that graduates should be able to create designs whose 'specifications could be wider than technical, including an awareness of societal, health and safety, environmental and commercial considerations'. Similarly, Accreditation Board for Engineering and Technology (2008) 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'. Engineering educators are consequently looking for ways to best help students develop problem-solving competencies. Pedagogies such as problem- and project-based learning are often used to help students learn to solve complex, open-ended design problems (Gibson 2003, Brodie 2009). Within problem-based learning, several methods have been used to structure student learning including teaching students design processes (Denayer *et al.* 2003), using explicit learning frameworks (Schultz and Christensen 2004), creating communities of practice (Pascual 2010) and teaching students problem-solving strategies (Woods 2000). Although many pedagogical approaches are being used, understanding of the approaches students use to solve problems is still quite limited.

The data presented in this paper draw from the first qualitative phase of a larger 3-year multi-methods study on open-ended problem-solving in engineering. It focuses on the language used by students as they describe their problem-solving processes while solving a complex, open-ended problem. Previous think-aloud studies of engineering problem solving in engineering have used a priori coding and have focused on the tasks that participants perform while solving problems (Atman *et al.* 1999, 2003, 2004, 2008, Adams *et al.* 2003). Here this previous work is extended by taking a constructivist approach, in which the focus is on how students describe their actions in their own words. This particular approach aids in capturing the complexity and richness of the actual problem-solving process as used by students. The purpose of the study was to investigate how engineering students solve engineering problems and what kind of processes they use to generate problem solutions. This study was guided by the following research question: How do engineering students describe the approaches and processes they use to solve open-ended engineering problems?

2. Review of literature

2.1. *Definitions of different types of problems, typologies*

The types of problems encountered by engineers have been classified in a number of different ways. One of the most basic classifications has been between well-structured and ill-structured problems (also commonly referred to as closed-ended and open-ended problems). Well-structured (or closed-ended) problems are those that are simple, concrete and have a single solution, while ill-structured (or open-ended) problems are complex, abstract and have multiple possible solutions (Jonassen 1997, 2000). Similarly, Kitchener (1983) describes well-defined problems as those with a single correct solution, while ill-defined problems are those 'for which there are conflicting assumptions, evidence, and opinion which may lead to different solutions' (p. 223). Kumsaikaew *et al.* (2006) argue that 'real world' (i.e. ill-structured) engineering problems are information-rich and thus require problem solvers to be able to reason effectively about what information is relevant to the task at hand.

Various aspects of ill-structured problems have been identified in the literature. For example, Shin *et al.* (2003) provide the following set of characteristics, stating that ill-structured problems:

- have more than one possible solution;
- fail to present one or more of the problem elements;
- have vaguely defined or unclear goals and unstated constraints;
- possess multiple solutions, solution paths or sometimes no solutions at all;
- possess multiple criteria for evaluating solutions;
- represent uncertainty about which concepts, rules and principles are necessary for the solution or how they are organised;
- offer no general rules or principles for describing or predicting most of the cases;
- have no explicit means for determining appropriate action;
- require learners to make judgements about the problem and defend them, often by expressing personal opinions or beliefs about the problem interpretation

Voss (2006) presents an overlapping set of characteristics of ill-structured problems and emphasises that solutions to ill-structured problems are neither right nor wrong but are judged in terms of plausibility or acceptability. This means that solutions to ill-structured problems are somewhat arbitrary and must be justified by the problem solver. As such, Voss (2006) emphasises that the knowledge, beliefs and attitudes of the problem solver play an important role in solving ill-structured problems.

Other authors extend the notions of problem types beyond the binary classification described so far. Johnstone (2001) classifies problems according to three binary variables: the data; the methods; the goals that are provided to the problem solver. According to this classification scheme, data may be either given or complete; methods may be either familiar or unfamiliar; problem goals may be either given or open. The three binary variables of this classification scheme result in eight potential problem types as illustrated in Table 1 (Reid and Yang 2002).

Jonassen (2000) extends this classification scheme by examining problems' underlying structure. He argues that problems vary in terms of structuredness, complexity and abstractness. Structuredness refers to the characteristics described above. Well-structured problems 'require the application of a finite number of concepts, rules, and principles being studied to a constrained problem situation' and are typical of the problems found in texts and on exams. In contrast, ill-structured problems 'are the kinds of problems that are encountered more often in everyday and professional practice…they are not constrained by the content domains being studied in classrooms, their solutions are not predictable or convergent' (p. 67).

Table 1. Problem types according to the classification scheme of Reid and Yang (2002)

Type	Data	Methods	Goals
1	Given	Familiar	Given
2	Given	Unfamiliar	Given
3	Incomplete	Familiar	Given
4	Incomplete	Unfamiliar	Given
5	Given	Familiar	Open
6	Given	Unfamiliar	Open
7	Incomplete	Familiar	Open
8	Incomplete	Unfamiliar	Open

Jonassen (2000) also proposed that 'problem difficulty is a function of problem complexity'. Complexity is determined by the size of the problem space – the number of branches at each node on the path to a solution as well as the depth of search required to reach a solution node. The level and breadth of knowledge required, the difficulty of the concepts involved and the degree of nonlinearity among variables are all factors that affect the complexity of a problem (Jonassen and Hung 2008).

The third defining characteristic of problems described by Jonassen is abstractness, or domain specificity. This term refers to the context in which the problem is placed and how that context affects transfer of a solution from one problem to another. Jonassen and Hung (2008) explain that: 'Most classroom problems are more abstract than most everyday problems, which are embedded in various contexts…Therefore, the more abstract the concepts required for understanding the problem and performing the problem-solving process, the more complex and difficult the problem is' (pp. 9–10).

Although there is a degree of similarity and connectedness between structuredeness, complexity, and abstractness, Jonassen (2000) argues that these characteristics 'are neither independent nor equivalent. There is sufficient independence among the factors to warrant separate consideration' (p. 66). Jonassen (2000) collected hundreds of problems and classified them by structuredness to create a typology of problem solving varying from well-structured problems to ill-structured problems. According to this typology, problems that are well-structured tend to be more abstract than those that are ill-structured. Complexity was found to be a largely independent characteristic of problem types. The original typology contained 11 problem types, which were later reduced to 10 by removing logical problems (Jonassen and Hung 2008).

Simon (1973), in contrast to Jonassen, describes a continuum of problem types. He argues that there is no clear boundary between well-structured problems and ill-structured ones. Rather, ill-structured problems are solved when they are reduced to a series of well-structured problems. In his view, most of the effort during problem-solving is aimed at reducing a problem in this way. Once this has been accomplished, a solution to the overall problem can be obtained by solving a series of individual well-structured problems.

2.2. *Strategies and teaching approaches for solving open-ended and ill-structured problems*

One of the primary distinctions between well-structured and ill-structured problems is the nature of a solution. Well-structured problems generally have a single correct solution, while ill-structured problems may have multiple possible solutions. Thus, it has been argued that distinct differences in approach are required for solving these two types of problems. This distinction of approach is highlighted by Woods *et al.* (1997), who define 'problem solving' as:

> the *processes* used to obtain a best answer to an unknown, or a decision subject to some constraints. The problem situation is one that the problem solver has never encountered before; it is novel. An algorithm or procedure to be used to solve the problem is unclear; problem solving requires much mental work. By contrast, the term 'exercise solving' refers to the 'recalling' [of] familiar solutions from previously-solved problems'. (p. 75)

Similarly, Simon (1981) coined the term 'satisficing' and argues that solving design problems is about developing satisfactory solutions rather than best possible solutions.

A large number of problem-solving strategies, or heuristics, for engineering are reported in the literature. Woods (2000) notes that few are based on research evidence and points out that some authors do not believe that problem-solving strategies are useful because the linearity (or step-by-step progression) described by many strategies is not actually followed in practice. Note that this is in contrast to other fields, such as medicine, where there is research to show that heuristics are a useful strategy (see, for example, Gigerenzer and Kurzenhauser 2005). Woods (2000) does argue, however, that strategies can be useful by providing scaffolding for problem solving. Two strategies based on empirical research are those of Jonassen (1997) and Woods (2000).

Woods (2000) reviewed more than 150 problem-solving strategies found in the literature while searching for a strategy to help engineering students at McMaster University. Woods (2000) eventually developed his own problem-solving approach with the purpose of helping students solve problems that are 'ill-defined' or 'atypical'. Thus, Woods (2000) makes a distinction between exercise solving and problem solving, arguing that:

> In *problem solving*, we must create a plan. We are unable to find a match between the current problem situation and our internal collection of problems we have solved successfully in the past; no immediate connection can be made between the given information and the goal. We tend to work backwards from the goal toward the given inputs. (p. 444)

Woods (2000) found that published strategies for solving complex problems can usually be represented as a series of sub-problems and that these sub-problems can be solved using what he calls a 'basic strategy'. He found that basic strategies proposed in the literature typically start with an 'awareness of problem' stage, move to a definition stage and close with an evaluation or verification stage. Woods refers to the application of a basic strategy to a complex problem (i.e. a collection of related sub-problems) as a 'nested' strategy. However, Woods points out that his problem-solving strategy is a basic strategy and not a nested one. This strategy is composed of six discrete steps, which can be used in a cyclical, or iterative, manner. Woods (2000) claims that findings in the literature, as well as experience with implementing his plan at McMaster University, have proven the effectiveness of the use of basic problem-solving strategies.

Jonassen (1997) has also developed a 'model' for solving ill-structured problems. This problem-solving process was influenced in part by Schön's (1990) writings on design as well as a think-aloud study of ill-structured problem solving by Sinnott (1989). Jonassen (1997) emphasises that his problem-solving model is a cyclical process and that problem solvers should adapt their strategies to the nature of the problem that they are solving.

More recently, approaches to problem solving that encourage students to develop their own processes for solving problems have been introduced into engineering education. Model-eliciting activities (MEAs) are a form of case based, team problem solving that focuses on eliciting from students conceptual models that they iteratively revise. Developed by mathematics education researchers to study the evolution of mathematical problem-solving expertise in middle school students, MEAs are increasingly used in introductory undergraduate engineering courses and are the subject of several National Science Foundation grants to expand their implementation (Hamilton *et al.* 2008). In an MEA, teams of students work together to solve a simulated real-world problem. In solving the problem, students must meet requirements as outlined by a fictitious client and the product of their work is evaluated against defined metrics, which determine how optimised their solution is. Students propose a model for solving the given real-world problem and then refine the model through an iterative process. According to Hamilton *et al.* (2008), the emphasis of MEAs is 'on *elicitation* and subsequent successive *alteration* and *generalization* of conceptual models' (p. 7). MEAs are a student-centred constructivist approach to education and thus aim 'to leverage the models and conceptual systems that the learner already possesses' (p. 10).

The primary focus of MEAs is not on a solution but rather on the process of arriving at a solution. MEAs require students to create a purposeful documentation trail of their problem-solving process, which has the benefit of allowing instructors to see the processes that students are using to solve problems and, as a result, gain a better understanding of students' conceptual misunderstandings. In contrast to providing specific rubrics for solving problems, the goal of MEAs is to elicit students' own strategies and help them to develop appropriate conceptual models, which can be used for problem solving.

A similar focus on process has occurred in the field of educational technology, where researchers have been developing open-ended learning environments (OELEs) as tools to help students learn to solve open-ended problems (Land and Hannafin 1997). OELEs are computer simulation environments that support student-centred, self-guided inquiry. Using OELE tools, learners construct conceptual models and receive real time, dynamic feedback about the effects of their actions on the model. Although the use of OELEs is intended to be self-guided, several studies have found that the use of OELEs is not likely to be effective if learners are left without external support during the learning process (Land and Hannafin 1997, Land 2000, Oliver and Hannafin 2001). Students using OELEs on their own often fail to use the simulation environment to evaluate the limitations of their mental models.

2.3. *What do we know about how people solve problems?*

Previous studies of problem solving have found that, in addition to problem structure, effective problem solving is dependent on domain expertise (Chi *et al.* 1988, Ericsson and Smith 1991), argumentation skills (Voss 2006), metacognition (Jaušovec 1994, Jonassen 1997), reasoning skills (Jonassen 1997) and affective variables such as attitudes and emotions (Isen *et al.* 1987, Schommer 1993, Pajares and Miller 1994, Blanchard-Fields 2007). Jonassen and Hung (2008) point out that in educational settings many of these factors are not under the control of the instructor but are learner dependent. How these factors affect problem solving can also differ between well-structured and ill-structured problems. For example, Shin *et al.* (2003) conducted a study with 124 ninth grade students comparing the problem-solving skills required for solving both well-structured and ill-structured astronomy problems. They found that domain knowledge and justification skills were significant predictors of scores on well-structured problems. With ill-structured problems, domain knowledge and justification skills were also found to correlate with solution scores. In addition, science attitudes and regulation of cognition (e.g. planning and monitoring skills such as modification of plans, re-evaluation of goals and monitoring cognitive efforts) were found to be significant predictors of scores on ill-structured problems.

Epistemic beliefs have also been found to influence students' problem-solving approaches. Schraw *et al.* (1995) developed and validated a 32-item instrument based on King and Kitchener's (1994) Reflective Judgment stage model of epistemic beliefs to test the relationship between epistemic beliefs and ill-defined problem solving. According to the Reflective Judgment model, students who are at a pre-reflective level have difficulty with ill-defined problems because they do not recognise the open-endedness of these problems, treating them as well-structured. Quasi-reflective students can recognise open-endedness, but have difficulties because they treat all knowledge claims as equally valid. At the highest level, reflective students are able to make judgements needed to solve ill-structured problems. In support of this model, Schraw *et al.* (1995) found that epistemic beliefs explained a significant proportion of variation in performance when solving ill-defined problems, but no such correlation was found between epistemic beliefs and performance when solving well-structured problems.

Many studies have explored the processes used by participants to solve open-ended problems – particularly design problems. These studies have made use of think-aloud methods to document the processes used by participants. Several of these studies have focused on comparing the processes used by novices and experts. For example, Atman *et al.* (1999, 2004) and Adams *et al.* (2003) compared the designs produced by 26 freshmen to 24 seniors as well as participants' design processes and found that seniors produced both higher quality and more sophisticated designs than did freshmen. In addition, seniors spent more time in problem scoping activities such as gathering information, considered a greater number of alternative solutions, transitioned more frequently between design steps and progressed further into the final steps of the design process. In a later study, the work of students was compared to that of practising engineers (Atman *et al.*

2007). Again, the quality of designs was found to increase with experience, and expert designers spent far more time in problem scoping activities than did student participants. Students also spent little time evaluating their solutions (Atman *et al.* 2004). In a related study, Adams *et al.* (2003) found that experts made many more moves between problem-solving stages than novices. This was interpreted as behaviour resulting from reflection-in-action, as proposed by Schön's (1983) reflective practitioner theory.

Verbal protocol studies of engineering design have also explored the use of visual representations such as sketching. Cardella *et al.* (2006) looked at when and how participants created and used sketching while working on a design problem. The researchers found that sketching was particularly important for supporting problem formulation. However, sketching was found to support each and every design activity that participants engaged in.

Ahmed *et al.* (2003) used ethnographic observations to compare the design processes of six novice and six experienced designers at an aircraft engine manufacturer. They found that novice designers tended to engage in trial and error behaviours and expressed uncertainty about many of the decisions that they made. In contrast, experienced designers engaged in a preliminary evaluation of a problem before implementing a design. Experienced designers were also more likely to consider relevant and interrelated issues while making decisions, refer to past designs, question data that they obtained, question the benefits of pursuing certain approaches and keep options open by demonstrating a willingness to reconsider discarded design processes if they were found to be useful at a later time.

2.4. *Summary*

The literature review above provides guidance for this study in a number of areas. First, a number of classification methods have been proposed to define problems. These range from lists of problem types that span from highly defined and constrained to highly open-ended, to classification of problems based on various characteristics that leads to a matrix of potential problem types (see, for example, Table 1). For this work, it has been found most useful to use the latter approach. Thus, the problem used in this study is considered ill-defined because it has a large number of critical decision points that must be considered in order to reach a solution, and because it is largely unconstrained.

The literature is full of approaches for solving problems and, as described above, many studies have examined how those approaches or elements of them are used by both students and experts. While this study take a constructivist approach to examine problem-solving processes as described by students, the results lend support for the use of systematic approaches to open-ended problem solving as described in the literature.

Finally, the literature discusses a number of factors that affect problem solving, with the focus generally on cognitive aspects. Of particular relevance to this study are the results showing how epistemic beliefs are related to ability to solve open-ended problems. As will be discussed below, the categories of problem solvers that emerge from the data lend support for epistemic beliefs as an important contributing factor.

3. Research method

3.1. *Theoretical perspective*

This study was guided by a constructivist theoretical perspective (see e.g. Guba 1990, Crotty 1998). From this perspective, the sources of knowledge are individual participants. Constructivism posits that individuals construct knowledge through interactions with their environment and that perceptions, understandings and realities are based on individuals' lived experiences (Crotty 1998, Kincheloe 2005, Cardellini 2006, Gordon 2009). Individuals are therefore seen as active knowers and reflections on lived experiences become integral to the data collection process (Schwandt 2001, Crotty 1998, Fosnot 2005). Furthermore, a constructivist perspective acknowledges that knowledge can be created, interpreted, recognised and contextualised differently by different individuals (Windschitl 1999). Because of such differences, the focus of a constructivist study is on the individual. In the context of the think-aloud method used in this study, students actively and in real time reflected on their thought processes and meaning making while solving the given engineering problem, thus contributing to knowledge about their problem-solving strategies and approaches.

3.2. *Problem-solving method*

The qualitative study presented in this paper explores the approaches taken by eight materials science students to solving a single open-ended engineering problem. This problem asked participants to develop specifications for 40 identical members of a truss bridge and then provide an estimate for the total cost of these members (the problem statement 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.

A think-aloud method was used to collect data on each student's problem-solving approach. That is, each student described their actions and thought processes aloud as they worked through the problem. These think-aloud sessions were video recorded and later transcribed for analysis.

To provide a quality measure of each participant's solution, the following rubric was used to evaluate participants' written solutions. The rubric was developed based on decision points that a problem solver would have to successfully traverse to produce a solution.

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.

3.3. *Population and sample*

Eight senior undergraduate materials engineering students from a large research intensive university in the south-eastern United States participated in this study. These eight participants are described in Table 2. This relatively small number allowed the research team to explore the experiences of these students in depth. While the limited number of students does not allow broad generalisation across additional engineering contexts, it does allow the researchers to explore the range of experiences within the context of materials engineering. (For a discussion of small sample sizes in qualitative research, see Merriam 1995.) Participants were recruited from among a total of 60 seniors in the Department of Materials Engineering based on the following criteria: students had to be materials engineering students, seniors and over 18 years old. Materials engineering students were chosen for this study because this is the disciplinary expertise of the principal investigator who developed the problem used in the think-aloud sessions. Participants recruited from

Table 2. Description of participants in the think-aloud

Participant	Problem-solving process description	Score	Prompts	Provided complete solution?
Amanda	Spent a significant amount of time conceptualising and considering alternative solutions during the problem-solving process. At several points spent time reflecting and rationalising her approach.	67%	1	No
Ashley	Solved the problem rapidly and systematically. Used the book to seek out information and then apply it to her problem-solving process. Rationalisations and reflections all seemed to help in the application of knowledge during the problem-solving process.	92%	0	Yes
Christopher	Spent a significant amount of time strategising and rationalising different approaches to the problem during his think-aloud session. Also accessed the book a great deal, but used it to help navigate the different pathways or strategies to solving the problem.	83%	0	Yes
Jessica	Spent a considerable amount of time accessing the book and conceptualising the problem.	58%	3	Yes
Joshua	Spent the least amount of time working on the problem, attempted no calculations, and provided only a partial solution to the problem. Accessed the book more frequently than many of the other participants. Spent much of his time considering alternatives and rationalising his approach to the problem.	25%	1	No
Justin	Carefully set up the problem and then spent a considerable amount of time struggling with calculations and rechecking his work. Was unable to provide a solution to the problem.	75%	1	No
Matthew	Spent the longest amount of time working on the problem and was unable to provide a solution to the problem. Spent considerable time accessing the book and moved frequently between calculating and reviewing concepts.	25%	4	No
Michael	Systematic and efficient in his problem-solving approach. Seemed to use the book only as a means to confirm or support his reasoning.	92%	0	Yes

a single engineering discipline also aid the study by helping to equalise domain knowledge (i.e. to avoid the potential effects of having participants with different domain knowledge). Seniors were recruited because of their academic experience and level of content knowledge in the subject area. The first eight students to express interest in participating were selected for this study. This study was focused on relating the problem-solving processes as expressed by the students to their performance on the problems and thus demographic data (e.g. ages, gender, race, GPAs, etc.) were not collected. The names of participants presented in this paper are pseudonyms. Approval for this study was obtained from the university's Institutional Reviewer Board. Each participant was compensated with a $60 gift card to a big box store for their participation.

3.4. *Data collection: think-aloud method*

A think-aloud method was used to collect data for this study. Participants were asked to verbalise their thoughts while conducting a specific task (van Someren *et al.* 1994). In this study, the task was solving an open-ended engineering problem. Think-aloud methods were developed in the field of cognitive psychology and are viewed as a means of gaining insight into mental operations from which conjectures can be made about the cognitive processing of participants (Ericsson and Simon 1993, Johnson 1993, van Someren *et al.* 1994). During the think-aloud process, participants are encouraged to constantly verbalise 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 verbalise everything that passes through their minds as they search for solutions to the problems they are working on.

Two researchers facilitated each think-aloud session. One researcher was responsible for setting up the video equipment and for taking observational notes during the think-aloud session. The role of the second researcher was to prompt participants at points where they were not giving adequate details on their thought processes or during extended periods of silence. Prompts included phrases such as, 'What are you thinking now?', 'How are you going to proceed from here?' and 'What have you decided to do at this point?' Prompts were never used to provide any information to aid the students in solving the problem.

Think-aloud sessions were conducted with individual participants. 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. Participants were then asked to practice thinking aloud with a simple unrelated exercise. During 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 solutions, a calculator and a copy of an introductory materials engineering textbook for use as a reference (Callister 2007). The participants' verbalisations 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. At the end of each think-aloud session, participants were reminded not to discuss their experience with their fellow students to avoid influencing the problem-solving approaches of other potential participants.

3.5. *Data analysis: script analysis*

Semantic script analysis was the primary method of analysis used in this study (Fonteyn *et al.* 1993, Funkesson *et al.* 2007). Semantic script analysis was used 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; (c) their problem-solving plan.

Recordings of the think-aloud sessions 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; (3) an assertion analysis. The first stage, or referring analysis stage, was used to identify nouns, or noun phrases, associated with decision points in participants' think-aloud processes. The script analysis stage involved categorising descriptions of participants' actions at associated decision points during the think-aloud sessions. This included actions such as 'conceptualising 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 – considerations 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; (5) declaratives – clear definitive actions or decisions articulated during the problem-solving process. Table 3 provides an example of an analysis worksheet generated by the researchers.

After completion of the 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 analysing across participants, patterns were investigated by comparing their referral, script and assertion analysis patterns.

Table 3. 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	Rationalising 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	Rationalising approach	Indicative

A third researcher prepared process diagrams of the solution paths for each participant based on the critical actions and decisions made by each participant. These critical actions and decisions correspond to the rubric items that were used to evaluate the quality of participants' solutions. In these process diagrams, oval objects represent decisions while rectangular objects represent actions taken. In a few cases, participants added unnecessary steps – such as applying a factor of safety – that are also reflected in the diagrams. These diagrams illustrate the decision points used in the script analysis.

4. Findings

Participants displayed various approaches to solving the given problem, of which some resulted in a viable solution while others did not. From the script analysis, three categories of problem-solving approaches emerged. The three problem-solving categories are the following:

(a) Extreme fixation and overwhelmed.
(b) Fixated and uncertain.
(c) Systematic and linear.

The participants' problem-solving approaches and corresponding solution scores are presented in Figure 1. It is important to note that the categories were based only on the script analysis and the solution scores were overlaid on the categories only after the categories were identified. The fact that the solution scores aligned with the categories created from the script analysis illustrates the robustness of the categories. The triangulation between these two different analysis approaches also supports the trustworthiness and credibility of the analysis and our findings (for more about triangulation as a validation strategy, see e.g. Mason 2002, Moran-Ellis *et al.* 2006).

The two participants with the lowest solution scores, Joshua and Matthew, exhibited extreme fixations, which hindered them from making important problem-solving decisions. 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, however, struggled with high levels of uncertainty. The three participants with the highest scores, Michael, Christopher and Ashley, all followed very systematic and linear approaches to the problem. They

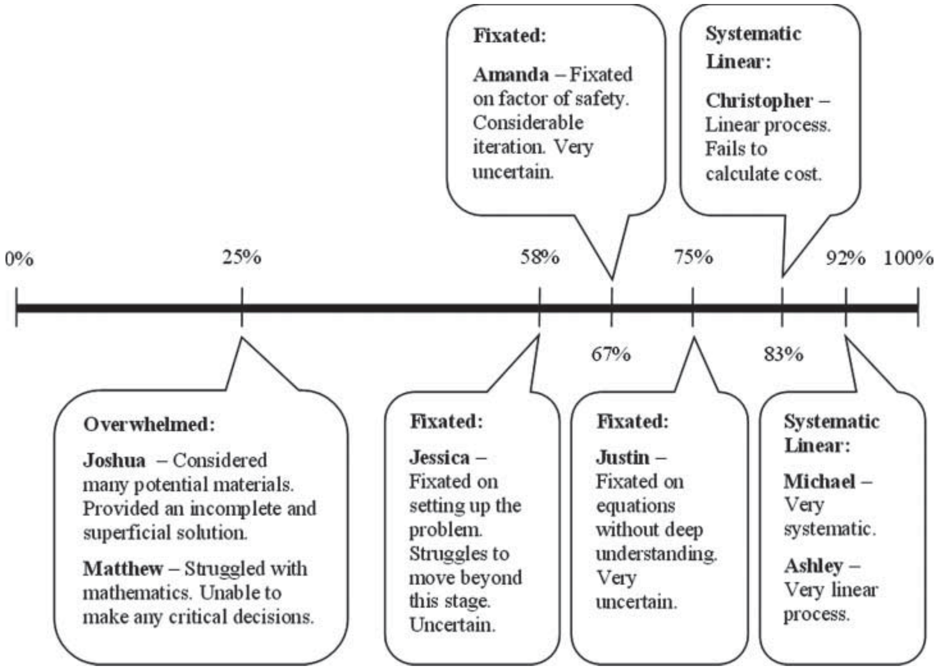

Figure 1. Participants' problem-solving approaches and solution scores.

avoided fixations and distractions and were able to identify critical decision points in the problem-solving process.

The following sections discuss these three categories of approaches, how these approaches emerged from the script analysis and the relationships between the approaches taken by each participant and the quality of their solutions.

4.1. *Extreme fixation and overwhelmed*

Both Joshua and Matthew struggled to progress toward a solution to the given problem. From the script analysis, it was clear that both became quickly consumed by a single problem-solving task. Neither Joshua nor Matthew provided a complete solution to the problem. Joshua spent all of his time considering various materials that he could specify for the bridge members. This pattern emerged from the script analysis as he moved between the three tasks of rationalising his approach, considering alternatives and applying knowledge. These three processes are evident in the following quote, during which Joshua was examining material property tables in the back of the textbook:

> 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.

At times Joshua appeared to be overwhelmed by the open-ended nature of the problem, exclaiming at one point: '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 materials in the textbook). No, no, no, no'. Joshua's referring phrase analysis illustrated that his vocabulary was not centralised around one unified theme or well organised. He used a variety of vocabulary terms including tension, strength, corrosion, yield, force, cost and mechanical properties. Additionally, his vocabulary patterns were

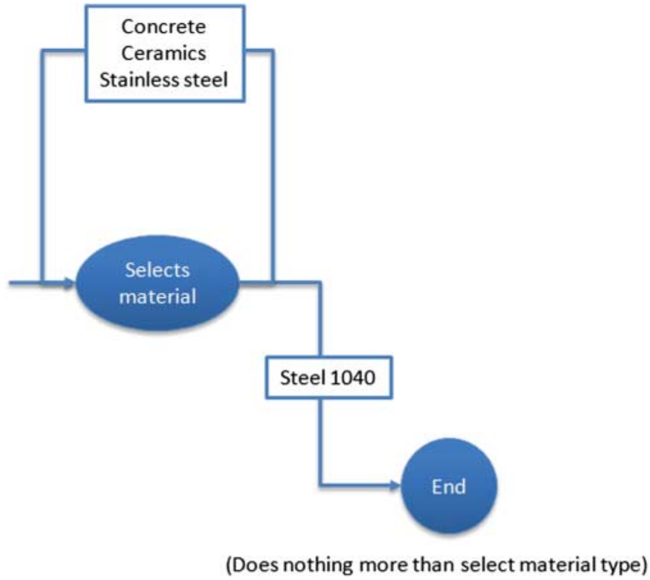

Figure 2. Joshua's solution path.

not distinctive, and repetitive and systematic uses of terms were mostly absent. His only repetitive vocabulary word was 'cost'. This lack of patterns and repetition could indicate that Joshua was not following a clear path to a solution.

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. This cyclical process seemed to be a result of uncertainty about the criteria he should use for making a material selection. As illustrated by the following quote, Joshua would begin to narrow down his selection to one material, but as he considered more criteria his decision-making process would unravel and he would go through the process of rationalizing his approach, considering alternatives and applying knowledge once again:

> 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. It's strong. [I'm] thinking it would be made—formed into something 12 feet long. 60 meganewtons is way below yield strength, any kind of limiting strength. This bridge could be made out of anything!

Joshua did finally select a material. However, he failed to specify dimensions for the bridge members or calculate a total cost for the job. Joshua appeared to lose sight of these other requirements of the problem because of his extreme fixation on material selection. Joshua spent significantly less time on this problem compared to the other participants and ended his problem-solving process abruptly.

Matthew also became severely distracted at the start of the problem-solving process and, like Joshua, was never able to progress to a complete solution. He spent all of his time attempting to develop a single unified mathematical expression that could be used to produce a solution to the problem. Because of this early distraction, his solution path is very simple (see Figure 3). Matthew's approach to the problem, like Joshua's, was also characterised by a repetitive pattern identified through the script analysis. Referring phrase analysis indicated that the vocabulary Matthew used mostly related to terms such as mass, stress, force, crack, density and corrosion. These terms were used as variables and thus his word use confirmed the findings from other aspects of analysis and pointed to his fixation with equation-driven problem solving. Additionally,

Figure 3. Matthew's solution path.

Matthew's vocabulary referred to a simple and technical conceptualisation of the problem rather than a creative problem-solving approach.

As Matthew worked to develop a mathematical expression to solve the problem, he followed a pattern of strategising, rationalising, trying some calculations and then reviewing concepts in the book. From the referring phrase analysis, it was also clear that Matthew was stuck in a cycle. Words such as 'maximum stress', 'mass', 'volume' and 'density' appeared again and again throughout the entire transcript. Through this cycle Matthew approached his calculations from several directions; however, he always ended up with a mathematical expression that was incomplete. He never recognised that the problem was not fully constrained due to its open-ended nature. After struggling for quite some time with various algebraic manipulations, 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 never stopped to take stock of the variables that were known and those that were not. Instead, he moved directly into algebraic manipulations failing to recognise that he needed to develop constraints of his own in order to solve the problem. As a result, Matthew was the only participant who did not make any critical problem-solving decisions.

From the assertion analysis, it could be seen that both Joshua and Matthew made many causal and declarative statements which, on their surface, appeared to indicate a high level of certainty about their problem-solving approaches. However, this certitude masked deficiencies in the approaches of these two participants. For example, Joshua very confidently talked himself out of providing cross-sectional dimensions for the bridge members arguing that:

> 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.

Joshua also made isolated and unsupported claims such as: 'Stainless steel would be too expensive'.

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 struggles 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.

This passage is full of short declarations, most of which are either false or contradictory, implying conceptual misunderstandings.

4.2. *Fixated and uncertain*

Jessica, Amanda and Justin exhibited fixations of various kinds as well as high levels of uncertainty or self-doubt. These participants, however, received higher scores for their solutions than the

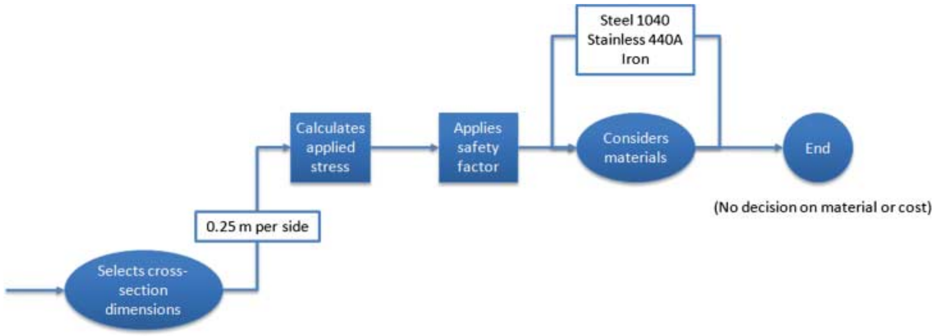

Figure 4. Jessica's solution path.

previous two participants because they were able to set up the problem correctly. The uncertainty of these participants appeared through the script analysis as rationalising and through the assertion analysis as connotative statements. 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 viable solution, but occurred only after a prolonged period of uncertainty, during which she struggled to set up the problem (Figure 4). Throughout almost the entire problem-solving session, Jessica was plagued by uncertainty and sought to rationalise each step of her problem-solving approach, as 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.

This quote also illustrates a discomfort with the open-ended nature of the problem and the subsequent need for assumption making. Although she set up the problem correctly, Jessica's uncertainty and fixation on problem set-up inhibited her from simply trying out some of the problem-solving steps that she was considering. In the end, Jessica's uncertainty kept her from making a material selection that would have allowed her to calculate a cost for the job. Additionally, Jessica's vocabulary choices mostly focused on materials selection. The words 'material' and 'cost' appear repeatedly and often in conjunction. As an example, Jessica stated that: 'it would be hard to calculate the cost because you are not given the cost of the material'. Only a few times while solving the problem did she mention words such as density, force and strength.

Amanda, in turn, considered more alternatives than the other participants and also exhibited more iteration between problem-solving tasks than the others. This is illustrated by the complexity of her solution path as shown in Figure 5. Although this iterative behaviour helped her find errors in assumptions and calculations, it 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 recognised the open-ended nature of the problem, but seemed to be unable to evaluate the quality of the solutions she was producing so that she could recommend one over another. Amanda also exhibited a fixation on incorporating a factor of safety into her solution although one was not required by the problem statement. Referring phrase analysis also supported Amanda's

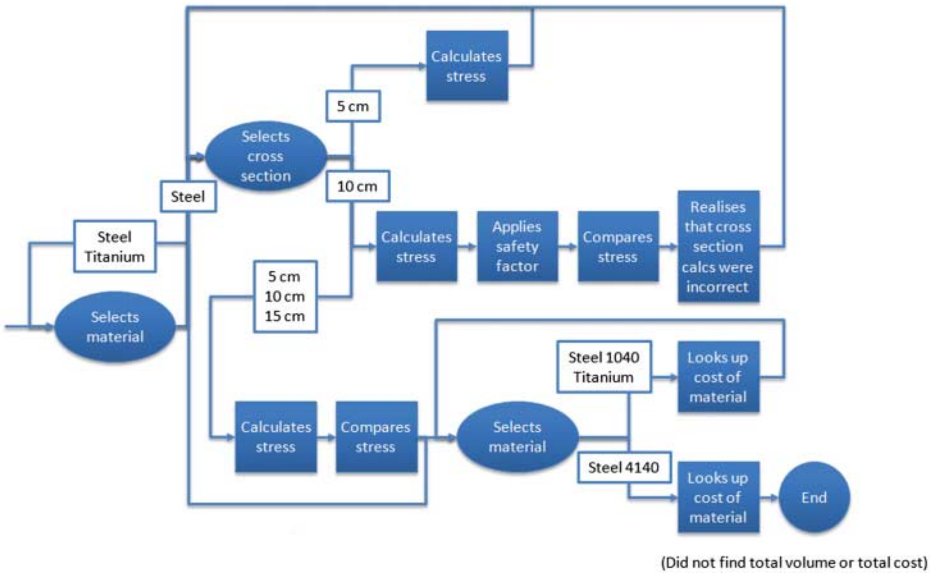

Figure 5. Amanda's solution path.

fixation with the concept of a 'factor of safety', which constituted one of her most frequently used terms during the problem-solving session. Repeatedly, she returned to considering a factor of safety wondering what value would be sufficient for the application presented in the problem. Amanda also referred to cost but was not able to make any conclusions about cost because she felt that she should first deal with her uncertainty regarding the factor of safety.

Amanda's fixation on a factor of safety carried through the entire problem. The following quote illustrates how Amanda grappled with this self-imposed criterion and how she sought to rationalize her decision-making process:

> 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 that was driven by a fixation on formulas and equations. After receiving the problem statement, he 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 (Figure 6). While Jessica and Amanda's uncertainty was exhibited through rationalisations, Justin's uncertainty can be seen through connotative statements such as the following:

> 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.

After obtaining values from his calculations, doubt would surface and Justin would repeat his calculations. Many of Justin's statements began with 'I guess…' Like Amanda, Justin was unable to find assurance that his solution was reasonable. Because of a fixation on trying various values

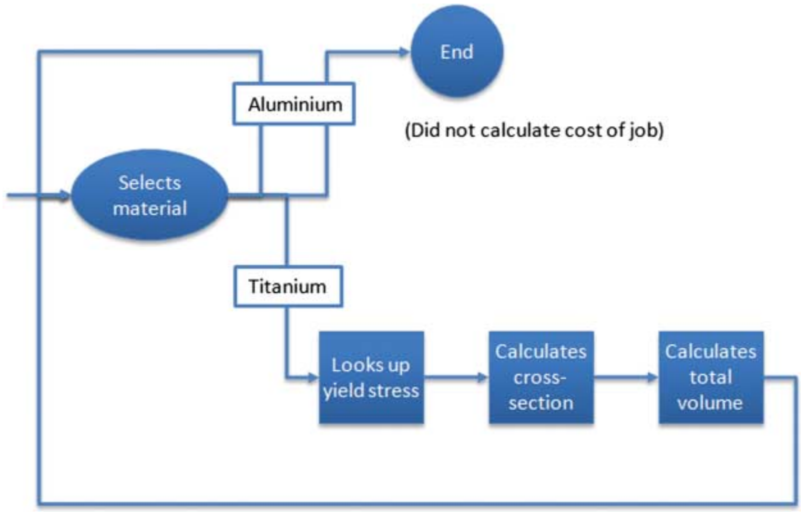

Figure 6. Justin's solution path.

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. Justin's vocabulary mainly focused on the main concepts of his equations. He continuously referred to concepts such as force, cost, stress, area, volume and material choices including metal, titanium and aluminium. He wanted to calculate the volume but did not have enough known variables and thus he felt that his calculation results did not make sense.

4.3. *Systematic and linear*

Christopher, Michael and Ashley's think-aloud data reveal very linear and systemic approaches to the problem. The script analysis revealed a pattern of studying the problem, rationalising an approach to the problem, applying knowledge and then calculating. The linear solution paths of these three participants are illustrated 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 three criteria: cost; strength; density. He arranged these values in a table to help him select a material that represented the most advantageous combination of the three criteria that he had selected.

The assertion analysis revealed that these three participants began many of their phrases with the word 'So…' The frequent use of 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 imply 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).

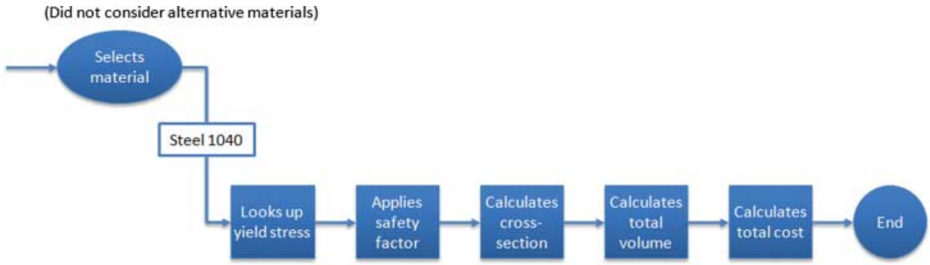

Figure 7. Ashley's solution path.

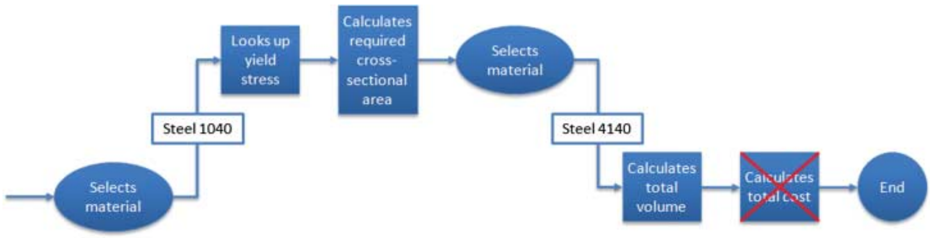

Figure 8. Christopher's solution path.

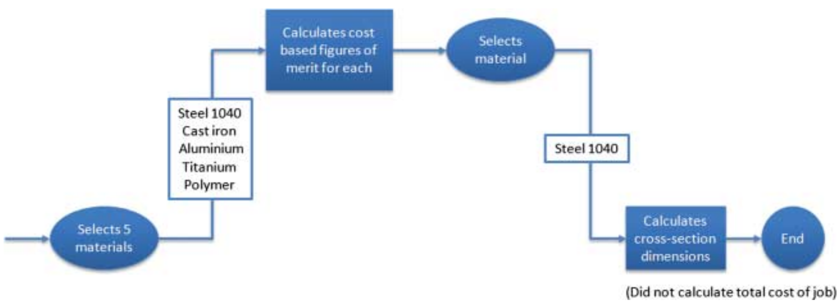

Figure 9. Michael's solution path.

The assertion analysis also revealed that 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 calculations: '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'.

Michael's referring phrase analysis pointed to his diverse vocabulary use. Similar to other participants he used terms such as cost, force, tension and density, but unlike others Michael drew upon more specific terms such as figure of merit. His vocabulary choices also indicated reflective and evaluative approaches to problems solving. Michael referred to 'reasonable area', 'wanting to minimise the mass', 'we'll have these parameters' and 'we will probably get a more exact answer'.

The linear and systematic approaches of Christopher, Michael and Ashley were also evident in the use of many causal and declarative statements as revealed through the script analysis. 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[they equal] 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. Her systematic and linear approach to problem solving also became visible when analysing her word choices and vocabulary. For example, Ashley did not repeat terms but moved from one term to another. At first she summarised her plan, including calculating the cross-sectional area, material selection and determining the cost. After she decided to use cold drawn steel, she referred to stress and force when calculating the area. Then she took into consideration the factor of safety, which led to a new size for the area. Later she was also concerned with density, which concluded her final calculations.

A purposefulness similar to Ashley's thought processes is 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.

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 to 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 he 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.

Christopher's referring phrase analysis exemplified a process of moving between calculating and conceptualising. He used terms such as tension, stress, force, density, volume and mass when trying to calculate the cost. When describing his conceptualisation processes, Christopher's vocabulary reflected his openness to unknown variables and assumptions accompanying those unknown variables. He referred to 'assuming the truss bridge', 'members could withstand the 60 meganewtons which is fairly significant' and 'then you have profit, you want maximum'.

5. Discussion

Three categories of problem-solving approaches emerged from the qualitative script analysis employed in this study. These three categories corresponded to participants' solution scores. The two participants in the first category both exhibited extreme fixations with a single problem-solving process, which inhibited them from producing a complete solution. Essentially, they were overwhelmed by the problem. Recall that solving open-ended problems requires the ability to identify and make critical multiple problem-solving decisions (Dym *et al.* 2005). The decision-making process is complicated by the nature of open-ended problems, which requires the problem solver to establish criteria that will be used for making critical problem-solving decisions. Joshua reduced the problem to one of arbitrary material selection, never moving past a stage of problem scoping (Atman *et al.* 2008) in which he struggled to decide which criteria to use for selecting a material. Matthew attempted to reduce the problem to an algebraic exercise. His efforts were ultimately unsuccessful due to the ill-defined nature of the problem and consequent lack of complete problem constraints. Matthew failed to recognise the ill-defined nature of the problem and that he had to develop some of the problem constraints himself. Matthew attempted to produce a single monolithic solution to the problem. He could have benefitted from engaging in a process of problem structuring, or breaking the ill-structured problem down into smaller well-structured problems (Simon 1973). Matthew's failure to break the problem down into smaller more manageable units may have resulted in cognitive (working memory) overload (Paas *et al.* 2004), as evidenced by exclamations such as: 'That doesn't seem to be working!' and 'I'm completely blanking out here right now'.

The strong causal and declarative statements made by Joshua and Matthew suggest that they had chosen (either consciously or unconsciously) to overlook critical elements of the problem. Joshua, in particular, made unsupported claims such as: 'It's got to be cheap' and, 'Concrete or like steel is what bridges are made out of'. These statements may be valid, but he left them unsupported. Argumentation is an important aspect of open-ended/ill-structured problem solving (Voss 2006) because it is the process of justifying problem-solving decisions.

The uncertainty of participants in the second category stands in contrast to the false sense of self-assurance of participants in the first. Jessica, in particular, was bothered by the need to make assumptions, at one point explaining: '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'. This uncertainty appears to result from a greater level of self-awareness during the problem-solving process. Dym *et al.* (2005) argue that designers must be able to handle uncertainty. Although participants in the second category struggled with uncertainty, the uncertainty was beneficial, in that it caused participants to evaluate their work. Like participants in the first category, participants in the second category each exhibited fixations of various kinds. However, these participants were able to make critical problem-solving decisions and, as a consequence, produced more complete solutions. The evaluative behaviour resulting from uncertainty may have been the factor that allowed these participants to progress further toward a solution.

The ill-defined nature of open-ended problems means that some constraints must be developed by the problem solver (Voss 1987, Jonassen 1997). The problem used in this study required participants to balance dimensional and loading constraints with other undefined constraints such as material properties and cost. The problem statement did not, however, limit participants to these constraints and some participants chose to add more. Two participants, for example, chose to incorporate a factor of safety. This self-imposed constraint proved to be a distraction, particularly for Amanda, who was uncertain about what value to choose. Although the problem asked participants to provide a total cost estimate, it did not specify cost as a constraint. Several participants, however, chose to use cost as a constraint. This is certainly not unreasonable. Simon (1981) notes that: 'Cost minimization has always been an implicit consideration in the design of engineering structures'. These participants had developed such a belief; however, there is no evidence to say where it came from.

Several of the participants in this study struggled to assess the quality of the solutions that they were developing. The criteria that participants would use to evaluate their solutions were not fully defined in the problem statement as this was an open-ended problem. This lack of criteria may have been a challenge for these participants. In their study of the design processes of engineering students, Atman *et al.* (2004) found that students tend to spend little time evaluating their solutions. This appeared to be the case for the lowest-performing participants in this study. Real-world engineering problems are information-rich and, as a result, engineers must be able to reason effectively about what information is relevant to the task at hand (Kumsaikaew *et al.* 2006). Many of the participants spent considerable amounts of time poring over material property tables in the back of the supplied textbook but struggled to decide how to use this information.

In a study comparing expert and novice engineering designers, Ahmed *et al.* (2003) found that novice designers tend to use trial and error methods. Woods *et al.* (1997) have also noted that many students are 'collectors of sample solutions' and that they try to solve problems by patching together various parts of previous solutions. Several participants in this study, particularly those in the second category, exhibited such behaviour.

The three most successful problem solvers in this study moved through the problem in a very systematic step-by-step progression. The relative ease with which these participants progressed through the problem may be a result of drawing on past experiences, existing mental models or problem-solving strategies. In a study comparing expert engineering designers to engineering students, Atman *et al.* (2007) found that the expert designers spent more time in problem scoping activities than other students. In an earlier study comparing the design processes of freshmen and senior engineering students, Adams *et al.* (2003) found that seniors made more transitions between various design tasks. They argue that these transitions may be indicative of a process of reflection-in-action (Schön 1983). Surprisingly, the most successful participants in this study had very linear solution paths. However, the solution path diagrams illustrate only the critical problem-solving decisions that were used to grade the quality of participants' solutions. They do not illustrate transitions between various problem-solving activities. The linear problem-solving approaches of these participants may also be a result of the structure of the problem used in this study. The problem statement did not explicitly ask participants to provide optimised solutions or to justify their solutions. As a result, there was no incentive for participants to refine their solutions. They could receive a high solution score regardless of the reasonableness of their solution.

The difficulty some participants had with the open-ended nature of the problem may 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 and Kitchener 1994), which defines three major stages of epistemological development: pre-reflective; quasi-reflective; 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'; however, '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 recognise that judgements can be made based on evaluation and interpretation of available evidence. From these descriptions, it can be hypothesised that students at the pre-reflective stage will have the most difficulty with open-ended problems because they see knowledge as being certain and do not recognise or understand how to deal with ambiguity. The three categories of participants in this study may represent the three levels of epistemic belief in the Reflective Judgment model. The two students with the lowest performance either did not exhibit uncertainty or did not recognise the ill-defined nature of the problem. These participants may be considered pre-reflective problem solvers. The three participants in the middle category all exhibited high levels of uncertainty. This reflects a level of awareness about the structure of the problem and, as such, these participants may be considered quasi-reflective problem solvers. The three top-performing participants all exhibited a level of ease while solving the problem and may be considered reflective problem solvers.

6. Conclusions

Participants in this study were grouped into three categories based on their approaches to solving the given 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 (and an inability to move forward in the problem space). These two participants made little progress toward a solution, becoming quickly derailed by their fixations. One participant got stuck in a materials selection loop while the other failed to recognise the open-ended nature of the problem and consequently embarked on an unsuccessful quest to develop a single mathematical expression that he could use to solve the problem.

Participants in the second category also exhibited fixations, although to a lesser degree. The approaches of these three participants were characterised by a high level of uncertainty, perhaps belying a greater sense of self-awareness than the participants in the first category. The lack of constraints provided by the problem statement was particularly disconcerting for these participants, as evidenced by the comments they made during their problem solving. Despite their uncertainty, these participants were able to progress further toward a solution than participants in the first category.

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-conceptualisations 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 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? How can students be helped to move beyond uncertainty? When solving open-ended problems, students must be able to identify and make critical problem-solving decisions, develop problem constraints and develop criteria for evaluating potential solutions. Jonassen and Hung (2008) suggest that a problem's difficulty must be matched to a learner's preparedness. Several participants in this study did not appear to be prepared for the open-ended problem that they were facing and may be 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. Students need opportunities to develop both strategies and an experiential base for solving open-ended problems (Woods *et al.* 1997; Woods 2000). Problem-based learning is a pedagogy that is structured around complex real-world problems and requires students to define and constrain the problems on which they work (de Graaf and Kolmos 2003). This kind of pedagogy has been found to positively correlate with the development of epistemic beliefs as well as conceptual understanding (Sahin 2010).

Diefes-Dux *et al.* (2004) and Hamilton *et al.* (2008) promote the use of MEAs to help students learn to solve open-ended problems. MEAs support the development of open-ended problem-solving skills through a focus on process rather than just product. Studies of technology-based self-directed constructivist learning environments developed to help students develop open-ended problem-solving skills have found that students using such learning environments resist conceptual change (Land and Hannafin 1997). Land (2000) suggests that the use of such self-directed learning environments may not be successful without external support. In contrast, the focus of MEAs is on team exercises in which students develop and refine conceptual models (Hamilton *et al.* 2008). The use of such activities may help students move to higher levels of epistemological development and give them greater comfort in dealing with the ambiguities of open-ended problems.

Think-alouds were used as the method of data collection in this study. Sheppard (2001) has noted that: 'there are few opportunities for us to observe our students while they are amid their design work' (p. 443). The use of think-alouds in this study has provided a view of the processes that students use while solving open-ended problems. Such observations of students while they are engaged in solving open-ended problems could be a valuable pedagogical tool that enables the assessment and reinforcement of problem-solving techniques and strategies.

The participants in this study appear to represent all three levels of epistemic belief of the Reflective Judgment Model (King and Kitchener 1994). The study is being extended to measure the epistemological beliefs of students and compare those beliefs to their ability to solve 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 and findings from these interviews will help to further explain the problem-solving approaches taken by the participants in this study. In addition, the larger study includes a quantitative component in which students' problem scores are correlated to potential predictors of problem-solving, including GPA, domain knowledge and working memory.

Acknowledgements

The authors wish to thank the National Science Foundation for their funding of this work through grant #DRL-0909976. They also thank the project advisory board for helpful guidance and suggestions: Ruth Streveler, Maura Borrego, Julie P. Martin, Aaron Kuntz and Andrew Conway.

References

Accreditation Board for Engineering and Technology, 2008. *2009–2010 Criteria for Accrediting Engineering Programs*. Baltimore, MD: ABET.

Adams, R.S., Turns, J. and Atman, C.J., 2003. Educating effective engineering designers: the role of reflective practice. *Design Studies*, 24 (3), 275–294.

Ahmed, S., Wallace, K.M. and Blessing, L.T., 2003. Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, 14 (1), 1–11.

Atman, C.J., *et al.*, 1999. A comparison of freshman and senior engineering design processes. *Design Studies*, 20 (2), 131–152.

Atman, C.J., *et al.*, 2003. The design processes of engineering educators: thick descriptions and potential implications [online]. *Expertise in Design: Design Thinking Research Symposium*. Available from: http://research.it.uts.edu.au/creative/design/papers/32AtmanDTRS6.pdf [Accessed 8 November 2012].

Atman, C.J., *et al.*, 2004. Comparing freshman and senior engineering design processes: an in-depth follow-up study. *Design studies*, 26 (4), 325–357.

Atman, C.J., *et al.*, 2007. Engineering design processes: a comparison of students and expert practitioners. *Journal of Engineering Education*, 96 (4), 359.

Atman, C.J., *et al.*, 2008. Breadth in problem scoping: a comparison of freshman and senior engineering students. *International Journal of Engineering Education*, 24 (2), 234.

Blanchard-Fields, F., 2007. Everyday problem solving and emotion. *Current Directions in Psychological Science*, 16 (1), 26.

Brodie, L.M., 2009. eProblem-based learning: problem-based learning using virtual teams. *European Journal of Engineering Education*, 34 (6), 497–509.

Callister, William D., 2007. *Materials science and engineering: an introduction*. New York: John Wiley and Sons.

Cardella, M.E., Atman, C.J. and Adams, R.S., 2006. Mapping between design activities and external representations for engineering student designers. *Design Studies*, 27 (1), 5–24.

Cardellini, L., 2006. The foundations of radical constructivism: an interview with Ernst Von Glasersfeld. *Foundations of Chemistry*, 8 (2), 177–187.

Chi, M.T.H., Glaser, R. and Farr, M.J., 1988. *The nature of expertise*. Hillsdale, NJ: Lawrence Erlbaum.

Crotty, M., 1998. *The foundations of social research*. Thousand Oaks, CA: Sage.

de Graaf, E. and Kolmos, A., 2003. Characteristics of problem-based learning. *International Journal of Engineering Education*, 19 (5), 657–662.

Denayer, I., *et al.*, 2003. Teaching a structured approach to the design process for undergraduate engineering students by problem-based education. *European Journal of Engineering Education*, 28 (2), 203–214.

Diefes-Dux, H.A., *et al.*, 2004. A framework for posing open-ended engineering problems: model-eliciting activities [online]. *Presented at the 34th ASEE/IEEE Frontiers in Education Conference*, Savannah, GA. Available from: http://fie-conference.org/fie2004/index.htm [Accessed 8 November 2012].

Dym, C.L., *et al.*, 2005. Engineering design thinking teaching and learning. *Journal of Engineering Education*, 94 (1), 103–120.

Ericsson, A. and Simon, H., 1993. *Protocol analysis: verbal reports as data*, revised edn. Cambridge, MA: Bradford.

Ericsson, K.A. and Smith, J., 1991. *Toward a general theory of expertise: prospects and limits*. Cambridge: Cambridge University Press.

European Network for Accreditation of Engineering Education, 2008. *EUR-ACE Framework Standards for the Accreditation of Engineering Programmes*. Brussels: ENAEE.

Fonteyn, M., Kuipers, B. and Grobe, S., 1993. A description of think aloud method and protocol analysis. *Qualitative Health Research*, 3 (4), 430–441.

Fosnot, C., 2005. Constructivism revisited: implications and reflections. In: C. Fosnot, ed., *Constructivism: theory, perspectives, and practice*, second edn. New York: Teachers College Press, 276-291.
Funkesson, K., Anbacken, E.-M. and Ek, A.-C., 2007. Nurses' reasoning process during care planning taking pressure ulcer prevention as an example. A think-aloud study. *International Journal of Nursing Studies*, 44 (7), 1109–1119.
Gibson, I.S., 2003. From solo-run to mainstream thinking: project-based learning in engineering design. *European Journal of Engineering Education*, 28 (3), 331–337.
Gigerenzer, G. and Kurzenhauser, S., 2005. Fast and frugal heuristics in medical decision making. *In:* R. Bibace, J.D. Laird, K. Noller and J. Valsiner, eds. *Science and medicine in dialogue*. Westport, CT: Praeger, 3–15.
Gordon, M., 2009. Toward a pragmatic discourse of constructivism: reflections on lessons from practice. *Educational Studies*, 45 (1), 39–58.
Guba, E., 1990. *The paradigm dialog*. Newbury Park, CA: Sage.
Hamilton, E., *et al.*, 2008. Model-eliciting activities (MEAs) as a bridge between engineering education research and mathematics education research. *Advances in Engineering Education*, 1 (2), 1–25.
Isen, A.M., Daubman, K.A. and Nowicki, G.P., 1987. Positive affect facilitates creative problem solving. *Journal of Personality and Social Psychology*, 52 (6), 1122–1131.
Jaušovec, N., 1994. Metacognition in creative problem solving. *In*: M.A. Runco, ed. *Problem finding, problem solving, and creativity*. Norwood, NJ: Ablex.
Johnson, M.K., Hashtroudi, S. and Lindsay, D.S., 1993. Source monitoring. *Psychological Bulletin*, 114, 3–28.
Johnstone, A.H., 2001. Can problem solving be taught? *University Chemistry Education*, 5 (2), 69–73.
Jonassen, D.H., 1997. Instructional design models for well-structured and III-structured problem-solving learning outcomes. *Educational Technology Research and Development*, 45 (1), 65–94.
Jonassen, D.H., 2000. Toward a design theory of problem solving. *Educational Technology Research and Development*, 48 (4), 63–85.
Jonassen, D.H. and Hung, W., 2008. All problems are not equal: implications for problem based learning. *The Interdisciplinary Journal of Problem-Based Learning*, 2 (2), 6–28.
Kincheloe, J., 2005. *Critical constructivism*. New York: Peter Lang.
King, P.M. and Kitchener, K.S., 1994. *Developing reflective judgment: Understanding and promoting intellectual growth and critical thinking in adolescents and adults*. San Francisco, CA: Jossey-Bass.
Kitchener, K.S., 1983. Cognition, metacognition, and epistemic cognition. *Human Development*, 26 (4), 222–232.
Kumsaikaew, P., Jackman, J. and Dark, V.J., 2006. Task relevant information in engineering problem solving. *Journal of Engineering Education*, 95 (3), 227.
Land, S.M., 2000. Cognitive requirements for learning with open-ended learning environments. *Educational Technology Research and Development*, 48 (3), 61–78.
Land, S.M. and Hannafin, M.J., 1997. Patterns of understanding with open-ended learning environments: a qualitative study. *Educational Technology Research and Development*, 45 (2), 47–73.
Mason, J., 2002. *Qualitative researching*, second edn. London: Sage.
Merriam, S., 1995. What can you tell from an N of 1?: issues of validity and reliability in qualitative research. *PAACE Journal of Lifelong Learning*, 4, 51–60.
Moran-Ellis, J., *et al.*, 2006. Triangulation and integration: processes, claims and implications. *Qualitative Research*, 6 (1), 45–59.
Mourtos, N.J., Okamoto, N.D. and Rhee, J., 2004. Open-ended problem-solving skills in thermal fluids engineering. *Global Journal of Engineering Education*, 8, 189–200.
Oliver, K. and Hannafin, M., 2001. Developing and refining mental models in open-ended learning environments: a case study. *Educational Technology Research and Development*, 49 (4), 5–32.
Paas, F., Renkl, A. and Sweller, J., 2004. Cognitive load theory: instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science*, 32, 1–8.
Pajares, F. and Miller, M.D., 1994. Role of self-efficacy and self-concept beliefs in mathematical problem solving: a path analysis. *Journal of Educational Psychology*, 86 (2), 193–203.
Pascual, R., 2010. Enhancing project-oriented learning by joining communities of practice and opening spaces for relatedness. *European Journal of Engineering Education*, 35 (1), 3–16.
Reid, N. and Yang, M.J., 2002. Open-ended problem solving in school chemistry: a preliminary investigation. *International Journal of Science Education*, 24 (12), 1313–1332.
Sahin, M., 2010. The impact of problem-based learning on engineering students' beliefs about physics and conceptual understanding of energy and momentum. *European Journal of Engineering Education*, 35 (5), 519–537.
Schwandt, T.A., 2001. *Dictionary of qualitative inquiry*, second edn. Thousand Oaks, CA: Sage.
Schommer, M., 1993. Epistemological development and academic performance among secondary students. *Journal of Educational Psychology*, 85 (3), 406–411.
Schön, D.A., 1983. *The reflective practitioner: How professionals think in action*. New York: Basic Books.
Schön, D.A., 1990. The design process. *In*: V.A. Howard, ed. *Varieties of thinking: Essays from Harvard's philosophy of education research center*. New York: Routledge, 111–141.
Schraw, G., Dunkle, M.E. and Bendixen, L.D., 1995. Cognitive processes in well-defined and ill-defined problem solving. *Applied Cognitive Psychology*, 9 (6), 523–538.
Schultz, N. and Christensen, H.P., 2004. Seven-step problem-based learning in an interaction design course. *European Journal of Engineering Education*, 29 (4), 533–541.
Sheppard, S.D., 2001. The compatibility (or incompatibility) of how we teach engineering design and analysis. *International Journal of Engineering Education*, 17 (4/5), 440–445.

Shin, N., Jonassen, D.H. and McGee, S., 2003. Predictors of well-structured and ill-structured problem solving in an astronomy simulation. *Journal of Research in Science Teaching*, 40 (1), 6–33.

Simon, H.A., 1973. The structure of ill structured problems. *Artificial Intelligence*, 4 (3–4), 181–201.

Simon, H.A., 1981. *The sciences of the artificial*, second edn. Cambridge, MA: MIT Press.

Sinnott, J.D., 1989. A model for solution of ill-structured problems: implications for everyday and abstract problem solving. *In*: J.D. Sinnott, ed. *Everyday problem solving: Theory and applications*. New York: Praeger, 72–99.

van Someren, M., Barnard, Y. and Sandberg, J., 1994. *The think aloud method*. London: Academic Press.

Voss, J., 1987. Learning and transfer in subject-matter learning: a problem-solving model. *International Journal of Educational Research*, 11 (6), 607–622.

Voss, J., 2006. Toulmin's model and the solving of ill-structured problems. *In*: D. Hitchcock and B. Verheij, eds. *Arguing on the Toulmin model: New essays in argument analysis and evaluation*. Berlin: Springer, 303–311.

Windschitl, M., 1999. The challenges of sustaining a constructivist classroom culture. *Phi Delta Kappan*, 80, 751–757.

Winkelman, P., 2009. Perceptions of mathematics in engineering. *European Journal of Engineering Education*, 34 (4), 305–316.

Woods, D.R., 2000. An evidence-based strategy for problem solving. *Journal of Engineering Education*, 89 (4), 443–460.

Woods, D.R., *et al.*, 1997. Developing problem solving skills: the McMaster problem solving program. *Journal of Engineering Education*, 86 (2), 75–92.

About the authors

Elliot P. Douglas is Associate Professor of materials science engineering, Distinguished Teaching Scholar and Dean's Fellow for Engineering Education at the University of Florida. He conducts research on engineering problem-solving, critical thinking, active learning, and the use of qualitative methodologies in engineering education research.

Mirka Koro-Ljungberg is a professor of qualitative research methodology at the University of Florida. Her research and publications focus on various theoretical and methodological aspects of qualitative inquiry, participant-driven methodologies, and cultural critique.

Nathan McNeill conducted this work while a postdoctoral associate at the University of Florida. He is currently an instructor in the Colorado Mesa University/University of Colorado Boulder mechanical engineering partnership program. He has a Ph.D. in Engineering Education from Purdue University.

Zaria T. Malcolm holds a Ph.D. in Higher Education Administration with a minor in qualitative research methodology from the University of Florida. Her current professional post is senior lecturer at the Excelsior Community College, Jamaica, with special responsibility for institutional strategic planning. Her research focuses on international education and qualitative research methods.

David J. Therriault is an Associate Professor in the School of Human Development and Organizational Studies in Education at the University of Florida. His primary research interests include the representation of time and space in language, the link between attention and intelligence, the use of perceptual symbols and embodiment, problem solving in engineering, and educational issues related to these topics.