Problem formulation within open-ended problems: looking through the Structure-Behavior-Function (SBF) and Novice-Expert (NE) Frameworks

Wan W. Amani. Wan Salim [a,b]*, Heidi A. Diefes-Dux[a]

[a]School of Engineering Education, Purdue University, 701 West Stadium Avenue, West Lafayette, IN 47907-2016, USA
[b]Department of Agricultural and Biological Engineering, 225 SouthUniversity Street, West Lafayette, IN 47907-2093, USA

Abstract

Problem formulation is integral to successful problem solving. To introduce problem formulation in first-year engineering classrooms, we utilize model-eliciting-activities (MEAs) – a client-driven engineering problems which guide students individually through problem formulation by asking three questions: Q1) “Who is the client?”, Q2) “In one or two sentences, what does the client need?, and Q3) “Describe at least two issues that need to be considered when developing a solution for the client.” The structure-behavior-function and novice-expert frameworks were used to analyse student responses before and after formal instruction on problem formulation was introduced. Student responses showed improvement with formal instruction.

Keywords: Problem formulation, structure-behavior-function, novice-expert, model-eliciting-activities;

1. Introduction

Engineers can be viewed as designers who engage in design activities (Dym et al., 2005; Pahl et al., 2007), and problem formulation is an integral part of a design activity (Cross, 2006; Pahl et al., 2007). In general, problem formulation is important when solving problems , and it often occurs at the initial stage in a problem solving process (Litzinger, 2011, 2010; Liikkanen, 2009; Schuyler & Skovira, 2008). Engaging in early problem formulationwas found to initiate better success in the succeeding problem solving stages hence it is acquired expertise ability (Voss and Post, 1988). Numerous researchers have described and studied the problem formulation process. In the Liikkanen (2009) heuristic model of problem solving, problem formulation starts with a designer interpreting a problem statement and defining a problem space. The Liikkanen (2009) heuristic model also states that evaluation of solutions often involves the designer referring back to the problem formulation stage, and that a strong problem formulation stage will enable the designer to better strategize the solution development. Litzinger et al., (2010) identifies problem formulation as problem recognition – a stage where one identifies a problem with a goal or a plan in hand. Their study on problem formulation conducted in a mechanical engineering statics class found that problem formulation stage affects the sketching of free-body diagrams and determination of equilibrium equations. Schuyler et al., (2008) studied the problem formulation activity of novices in a beginner computer science course and listed specific activities involved in problem formulation. This list includes “abstraction” – a process to extract only relevant details. Pólya (1945, 1957) defined problem formulation as efforts to comprehend the problem statement, such as understanding the terms involved and restating the requirements. Allen (1995) believes problem formulation requires one to select the correct problem or situation. We could summarize that problem formulation consists of activities that require one to interpret, comprehend, and select relevant details from a problem description.

In our study, we investigate the problem formulation ability of first-year engineering students as they solve a special class of open-ended, authentic, client-driven problems called model-eliciting-activities (MEAs). In MEA, students were given a problem description that establishes a context in which multiple stakeholders care about the

* Wan Wardatul Amani Wan Salim. Tel.: +1-765-350-0133
E-mail address: asalim@purdue.edu

solution to a problem. Further, a set of data is provided to used as a basis for developing a generalizable mathematical model for the stakeholders; this set of data functions as the constraints on solution development. Students are required to individually answer three questions before they engage in the team activity of solving the problem. These questions are: Q1) “Who is the client - the direct user of your procedure?”, Q2) “In one or two sentences, what does the client need?”, and Q3) “Describe at least two issues that need to be considered when developing a solution for the client.”. These questions were initially conceived as a “test” of students’ reading comprehension of the problem text. However, they can be utilized to study students’ problem formulation abilities. In this study, we refer to problem scoping and problem identification as subcomponents of problem formulation. Q1 and Q3 have the nature of problem scoping, while Q2 has the nature of problem identification. Problem scoping is the activity of discerning relevant details from available information in a problem description. Here, Q1 initiates one to think about whom among the stakeholders needs the solution being requested, and Q3 requires one to consider relevant issues about the task-at-hand, before diving in solution formulation. Q2 has the nature of problem recognition – one identifies the needs and extracts relevant details before solution development. Q2 requires one to engage in an analysis of the needs of the client/direct user via the problem text, before solution formation. According to Fricke (1999), the problem formulation stage allows one to clarify important information from problem descriptions that are considered vague or incomplete. One clarifies goals to be accomplished and establishes measures for achieving the goals. Hence, ignoring or discarding the problem formulation stage can result in the “right” solution to the wrong problem (Nadler, Smith, & Freya, 1989).

Owing to the impact of effective problem formulation on problem solving as a whole, there needs to be practical strategies to enhance both teaching and learning of problem formulation in the engineering classrooms. To develop practical strategies, we analyzed students’ problem formulation responses to the MEA individual questions through the structure-behavior-function (SBF) and novice-expert frameworks. The SBF framework was introduced by cognitive scientists (Hmelo-Silver & Pfeffer 2004; Vattam et al., 2011) and has been applied to cognition studies in computer science courses (Goel, Rugaber & Vattam, 2009) and the assessment of student learning (Chan, Wu, & Chan, 2010). The SBF framework effectively describes a complex system with different layers of organization by looking into the roles played by the elements of the system. A complex system could not be explained by linear casual reasoning. An example of complex system is an ecological system, which consists of many levels of organization such as genes, individuals, populations, species, and so on, up to the larger environment. The SBF framework helps explain the interactions between the different levels of organization in a complex system. The goal of the SBF framework is to connect the structure of a system to its behavior (mechanism) and function (the system output or outcome) (Hmelo-Silver & Pfeffer, 2004; Vattam et al., 2011). In our research, we first code students’ responses to Q2: “In one or two sentences, what does the client need?” using a scheme based on the SBF framework. Then we represent the codes in a descriptive node tree (DNT) which visually shows the students’ collective responses with different levels of branching depth in the vertical or horizontal direction.

To analyze students’ response, we also look into the differences between expert and novice problem solvers to qualitatively describe students’ responses to the individual questions. There has been interest in characterizing the nature of expert problem solving and comparing of expert and novice problem solving approaches (Cross, 2004). One interest has been in the qualitative differences between expert and novice ability to problem formulate and problem scope. Experts were found to be better at interpreting problem descriptions, and they have a clearer understanding of the problem. Atman et al., (2008) found that experts have a breadth-type approach while novices have a more depth-type approach to problem formulation. In other words, experts look more into the context of the problem during the problem formulation step, while novices spend more time in solution development. Experts provide more logistical details (related to the management of the flow of information and goods (e.g., cost(, technical factors, and more relevant details (Kilgore, Atman, Yasuhara, & Morozov, 2007). Furthermore, experts were found to iteratively revisit the problem formulation stage during solution development (Adams & Atman, 1999; Hjalmarson, Cardella, & Adams, 2007). According to Liikkanen (2009), effective problem solvers often evaluate their solutions by referring back to their problem formulation stage. Experts also spend more time in problem formulation (Atman et al., 2007). In addition, researchers found that many of errors in novices' solutions in comparison to experts' solutions were due to inadequate and ineffective problem formulation (Chi, Feltovich, & Glaser, 1981; Adams, Chimka, Bursic, & Nachtman, 1999). Finally, expert-novice differences are magnified when the nature of a problem is ill-structured and open-ended as these problem types require a more elaborate problem formulation approach (Voss & Post, 1988).

The goal of this study is to compare first-year engineering students' responses to the guided problem formulation and problem scoping questions (Q1-Q3) before and after formal instruction on problem formulation was introduced into a required course. The results could inform the design of effective strategies for teaching problem formulation and make the learning of problem formulation transparent and available for assessment and feedback.

2. Methods

2.1. Course information and setting

The setting for this study was the Fall 2007 and Fall 2008 offering of a required first-year engineering problem solving and computer tools course with an enrollment of approximately 1500 students at a mid-west university. The course was a coordinated mix of introduction to engineering problem solving and teaming, engineering fundamentals, and computer tools for solving engineering problems (Diefes-Dux & Imbrie, 2008). In Fall 2007, course meetings included two 50-minute faculty led lectures (N~450) and one 110-minute graduate teaching assistant (GTA) led lab period (N~28) per week. In Fall 2008, course meeting included a paired 110-minute lecture and 110-minute lab each week (N~120). Each lab period was handled by four GTAs with the help of two to four undergraduate teaching assistants (UGTAs) (Verleger, et al., 2010).

2.2. MEA implementation

Three Model-Eliciting Activities (MEAs) were implemented in Fall 2007: MEA 1 - Theft Prevention with Laser Detection; MEA 2 - Just-in-Time Manufacturing; and MEA 3 - Nano Roughness. Three model-eliciting-activities (MEA) were also implemented in the Fall 2008: MEA 1 – Purdue Paper Airplane Challenge, MEA 2 - Just-in-Time Manufacturing; and MEA 3 – Travel Mode Choice. Each of these MEAs was used in this course in one or more prior semesters (Zawojewski, Diefes-Dux, & Bowman, 2008).

In Fall 2007, GTAs received significant general and MEA-specific training prior to the start of the semester and prior to each MEA implemented in the course (Diefes-Dux, et al., 2008). With regard to the development of students' problem formulation abilities, no explicit training was provided other than a relatively quick review of the desired answers to the three individual questions associated with each MEA. This review was done only so that GTAs could grade student responses. The primary focus of the GTA training was on MEA implementation in the lab (e.g., how to address student questions, how to ensure students are on task) and assessment of the student teams' solutions to the client's problem. In Fall 2008, GTAs participated in 8 hours of MEA training split across two days one week prior to the start of semester. They worked in teams on a MEA and were taught the six principles of MEA design and its application to classroom instruction. They were introduced to the feedback and assessment rubric and practiced using the rubric by applying it to actual students' responses from prior semesters, this included student responses to the individual questions Q1-Q3 and team solutions to the MEA. They also had access to online professional development materials, where they continued to practice evaluating and assessing student responses and compared their assessments to that of a MEA expert (Verleger, et al., 2010). This continued practice also encompassed both evaluation and assessment of student responses to the individual questions Q1-Q3 and team solutions to the MEA.

During one faculty-led lecture period prior to the launch of the first MEA of the semester, the first-year engineering students worked through a sample MEA. The purpose was to set expectations for the GTAs' and students' roles in the lab, student engagement in working on the MEA, and quality of student team work on the MEA. In Fall 2007, no instruction was specifically targeted at problem formulation, though the answers to the three individual questions associated with the sample MEA were reviewed but not discussed in detail. In Fall 2008, instruction was provided on problem formulation. This instruction consisted of answering and discussing appropriate responses and strategies for composing a response to Q1 through Q3 using the context of the sample MEA. For Q1, faculty members walked student through a listing of the stakeholders that are affected by the problem. Students were also asked to identify from the stakeholders list the client, defined as the direct user. In other words, one of the stakeholders is the client/direct user who will use the team's solution. These stakeholders can be direct-, indirect- or non-clients/users. For Q2, faculty members introduced the students to an anatomy of good response. A good response includes the following elements:: the deliverable – a "thing" for the client, the criteria for success – what is the solution trying to achieve, and constraints – what bounds the solution, which is often the given data. For Q3, students were asked to problem scope, or think about issues related to solving the problem. Faculty members guided students to think about issues that affect the client/direct user. Hence, issues that affect only indirect clients or non-clients are considered out of scope.

Each MEA was launched in a lab setting. Students individually read the MEA problem statement. The statement consisted of two components: 1) a story (e.g. newspaper article, company profile, background information, etc.) that sets the larger context for the problem and 2) a memo directed to the student team from someone in a supervisory role at a fictitious company describing the client and client's problem. Based on this reading, students individually answered the three questions Q1-Q3. Typically, students took 15-20 minutes to complete the reading and individual questions. The questions were answered through an online MEA tool. The web-based MEA tool coordinated feedback from peers and GTAs on students' responses and provided a means of recording students' work for data collection (Zawojewski, Diefes-Dux, & Bowman, 2008).

Once all team members completed the individual questions, the team gathered to come to consensus on the individual questions and then developed and submitted their first draft solution to the client's problem. The solution to a MEA is a generalizable mathematical model (procedure) that the client can use to solve the client's problem. The nature of MEAs and their implementation is such that students are encouraged to evaluate their own solutions and go through cycles of expressing, testing, and revising. In the following week, via the online system, the GTAs provided feedback on and assessment of the individual questions and the first draft of the team solution. Through a series of outside-of-class homework assignments lasting 4to 6 weeks, student teams revised their team solutions to the client's problem based on GTA and peer feedback (Verleger & Diefes-Dux, 2008).

2.3. Just-in-time manufacturing MEA description

For the *Just-In-Time Manufacturing (JITM)* MEA implemented in Fall 2007 and Fall 2008, student teams were required to use their knowledge of shipping and statistics to develop a procedure to rank shipping companies in order of most to least likely able to meet shipping needs based on historical data concerning late arrival times. In both Fall 2007 and Fall 2008, the students were provided with a company profile, memo detailing the immediate task, and data set (see Appendix).

2.4. Coding and analysis of students' responses

Student responses to the individual questions from one lab section per GTA were selected for inclusion in this study. As each GTA led multiple sections, their second or third section taught was selected for inclusion in this study to minimize the impact of first-time implementation. Individual students' responses to Q1 (who is the direct client – the direct user of your procedure), Q2 (what does the client need) and Q3 (what are two issues to consider) for the

JITM MEA for students' responses in Fall 2007 (n = 468), and Fall 2008 (n = 482) were analyzed using open-coding and content analysis. Responses generated after collaboration within the four-person teams were not used in this study. Three levels of coding activity were implemented. As suggested by Creswell (2008) & Patton (2002), student responses were first read to get a general feel for the data and to start developing codes. Codes were informed by the text of each MEA and the language and concepts associated with engineering design and problem formulation. A second reading consisted of actually assigning codes by searching for repeatable regularities (Miles & Huberman, 1994). To assign codes, "like-minded" pieces were put together in "data clumps," as suggested by Glesne (1999). The codes from the second reading were refined and applied to the data in subsequent readings. Finally, these codes were mapped to the novice-expert and SBF frameworks.

The coding scheme for Q1 consists of four categories: 1) direct clients, those who will use the needed deliverable, 2) indirect clients, those who will use or benefit from the needed deliverable only indirectly, 3) non-clients, those who will not use the needed deliverable or are unknown entities, and 4) multiple clients, combinations of 1-3. These client categories emerged from the MEA text which introduced students to several stakeholders. The purpose of presenting students with multiple stakeholders is to engage them in a realistic problem solving context – to think about who are the stakeholders that are impacted by their solution. From a problem formulation perspective, this means that students must obtain information from reading the texts, discern the proximity of various stakeholders to the solution, and identify the direct client – the person(s) who will actually use the team's procedure. Although there is a correct answer to Q1, the activity has the nature of problem scoping. When information gathering during a problem scoping activity, one identifies various stakeholders (e.g., users, businesses, administrators, manufacturers, society) and relates the relevancy of each stake holder to the problem by discerning their roles. Students' responses to this question provide a window into the nature of their problem scoping.

For Q2, a coding scheme emerged that breaks students' responses into elements that map to the SBF framework. To make sense of the data based on this framework, the words used by students were mapped closely to those in the SBF literature. The SBF elements are: (1) the structure – the deliverable or the "thing" required by the client, (2) the structure behavior – the characteristics of the deliverable or what makes the deliverable achieve its function, (3) the structure function – the purpose of the deliverable, (4) the function behavior – describes how the deliverable function acts/behaves, and (5) the constraints - what bounds the structure when achieving its function. In SBF framework, the purpose of subcomponents to a larger system are described, thus allows effective reasoning to be made on the mechanism that enables function and causal roles played by structural elements. To visualize differences in students' interpretation of the client's problem and the level of detail in students' problem identification, descriptive node trees (DNTs) were developed. A DNT for student responses' to Q2 for the *JITM* MEA is shown in Figures 1. Not all students' responses contained all five identified elements. That is, while all responses contain at least one structure, the structure may be described in no or only partial detail. In other words, students do not necessarily articulate a behavior or function for a structure; nor do they necessarily provide constraints. In order to utilize the node tree representation clearly, responses containing multiple deliverables were omitted. These multiple deliverable responses represented only 9.4% of the total student responses in Fall 2007 and 15% of the total student responses in Fall 2008. Percentages shown in the DNTs represent the number of codes taken over the total number of students who provided a single deliverable (n= *424*and n= *409* for Fall 2007 and Fall 2008, respectively). Only code counts above 10 are included in the DNT. The purpose of Q2 is for students to identify the client needs, which are loosely described in the problem text, but must be teased out by focusing on the structural element or deliverable that the team is actually being asked to develop, its behavior(s)/characteristic(s), its function(s), its function(s) behavior, and constraint(s). When students provide more structure elements in their responses, the tree is wider in the vertical direction. When the structure element is associated with its function, the tree is wider in the horizontal direction. Furthermore, an element of constraint that bound the solution add depth to the tree in the horizontal direction. The behavior associated with a structure is a branch out from the structure element. If the structure element is associated with more behavior elements, the branching from the structure is longer in the horizontal direction.

For Q3, a coding scheme was developed to categorize students' responses. These categories are: 1) restatement of the problem – issues that are raised from by reiterating/copying the problem text, 2) context-level issues – issues pertaining to the context of the problem and are usually big picture issues, and 3) task-level issues – issues pertaining to specific tasks required for solution development. These issues can be derived by thinking about the direct client/direct user needs. To think about task-level issues, students should refer back to their responses to Q1 and Q2. For Q3, since students provide multiple issues of mixed quality, each issue raised in a student response was coded independently based on the aforementioned categories. Students' responses were further categorized into combinations of the three categories: restatement of the problem, task-level issues, and context-level issues. The purpose of Q3 is to begin to get students oriented to the data and information that they have to work with to solve the problem; this question is intended to draw out another perspective on the scope of the problem that goes beyond Q2. Students need to sort through the information in the problem and their own thinking, backgrounds, and knowledge of the problem context, and the concepts and methods that they might use to solve the problem (Atman. et al., 2008).

3. Results and Discussions

3.1. Q1 – "… Who is the client/direct user?".

Tables 1 and 2 show the counts and percentages of student responses to Q1 for Fall 2007 and Fall 2008, respectively, that were coded in each category with code descriptions and sample student responses. For Fall 2007, results show indirect clients were identified as the user of the requested procedure in 87.0% of the responses, while in 19.8% of the responses multiple clients were identified and in 12.6% of the responses non-clients were identified. There was no direct client identified in the student responses. For Fall 2008, results show 57.5% of the student responses identified the direct client. In the multiple-client category, most student responses included a combination of indirect-clients in Fall 2007 (5.3%), while most student responses included direct-clients together with the indirect-clients in Fall 2008 (3.1%). The percentage of non-clients combination in the multiple-client category of Fall 2007 exceeds that of Fall 2008 by only 2.0%.

Table 1. Q1 – "Who is the client?" client types found in student responses for Fall 2007.

Client Type	**Code Description**	**Student Examples**	**Counts (Percentage out of *n=468*)**
Direct Clients	NA	NA	NA
Indirect Clients	CEO of Devon Dalton Technologies Devon Dalton Technologies (DDT)	*"The client is Devon Dalton, the CEO of D, Dalton Technologies."* *"The client is D. Dalton Technologies."*	407 (87.0%)
Non-Clients	Non-clients include the subsidiaries Ceramica and Alphalon, and another team that was assigned by the CEO Devon Dalton.	*"The Alphalon and Ceramica Divisions of D. Dalton Technologies."*	13 (2.8%)
Multiple Clients	A combination of indirect clients	*"The client is Devon Dalton and his company, DDT."*	25 (5.3%)
	A combination of indirect clients and non-clients	*"D.Dalton Technologies, Ceramics and Alphalon."*	10 (2.1%)
	A combination of non-clients	*"The Alphalon and Ceramica Divisions of D. Dalton Technologies."*	13 (2.8%)

Table 2. Q1 – "Who is the client?" client types found in student responses for Fall 2008.

Client Type	**Code Description**	**Student Examples**	**Counts (Percentage out of *n=482*)**
Direct Clients	Logistic manager, Logistic Manager at DDT	*"The client is the company's Logistics Manager."*	277 (57.5%)
Indirect Clients	CEO of Devon Dalton Technologies Devon Dalton Technologies (DDT)	*"The client is D. Dalton Technologies." "Devon Dalton."*	148 (31%)
Non-Clients	Non-clients include the subsidiaries Ceramica and Alphalon, clients not mentioned in the problem statement (e.g. managers at DDT, workers at Ceramics or Alphalon) and generic clients (e.g. people who will read the procedure)	*"The Alphalon and Ceramica Divisions of D. Dalton Technologies." " The employees of the Alphalon company" "The client is the group of people who will read our procedure and directly use it to determine who the best company is."*	15 (3.1%)
Multiple Clients	A combination of direct client and indirect client	*"The client is DDT and the Logistics Manager to identify a new shipping company."*	16 (3.3%)
	A combination of direct clients and non-client	*"The client is the logistics manager and the staff at DDT, Ceramica, Alphalon who will be affected by the lateness of products arriving to the place of assembly."*	4 (0.8%)
	A combination of direct client, indirect client, and non-client.	*"The client is D. Dalton Technologies, the Logistics manager, Ceramica, and Alphalon."*	1 (0.2%)
	A combination of indirect clients.	*"The client of this procedure will be DDT, but more specifically Devon Dalton."*	4 (0.8%)
	A combination of indirect client and non-client.	*"Dalton is the client. More specifically, the logistics manager for Dalton is the ultimate user."*	14 (2.9%)
	A combination of non-clients.	*"The workers of DDT, the makers of the piezoelectric devices."*	3 (0.6%)

3.2. Q2 – "… what does the client need?".

Table 3 lists the structure-behavior-function element descriptions and student response examples. The examples of student' responses listed in Table 3 refer to the DNT shown in Figure 1 (e.g. Figure1, A corresponds to the branch of the DNT labelled A). The DNT shows patterns that emerged from students' response for both Fall 2007 and Fall 2008 semesters, with counts and percentage for the latter year being underlined.

The structure: There are five structures or deliverables identified in students' responses from both years: 1) *a procedure*, 2) *a shipping company – or shipping companies, 3) a ranking of shipping company, 4) an analysis of shipping company or an analysis of shipping companies' data*, and5) *others*. In Fall 2007 and Fall 2008, *a procedure* was identified as the deliverable in 69.6% and 81.2% of the student responses, respectively. The deliverable *a shipping company – or shipping companies* was identified in 14.6% and 6.8% of student responses from Fall 2007 and Fall 2008, respectively. In Fall 2007, students provided shipping company as the deliverable in their response twice to that provided in Fall 2008. In Fall 2008, students provided more deliverable in the *others* category.

Structure behavior. The structure *a shipping company or – shipping companies* is associated with the structure behavior *reliable* in 12.0% of the students' responses in the Fall 2007 semester and in only 4.4% in Fall 2008. The structure *shipping company – or shipping companies* is also associated with the structure behavior *meet timing needs* in 8.7% of the response in Fall 2007 and in 4.4% of the responses in Fall 2008.

Structure function. From the structure *procedure,* students identified either the function *to rank shipping company* or *to choose shipping company*. For the function *to rank shipping company*, 24.8% in student responses were from Fall 2007, and 37.2% in student responses were from Fall 2008. For the function *to choose shipping company*, 14.2% in students' responses were from Fall 2007, and 44.0% in students' responses were from the latter year. There is no function associated with the structures *shipping company – or shipping companies, ranking of shipping company, analysis of shipping data and others,* or the counts of students' responses in these structure categories that include the structure function are lower than 10.

Function behavior. The deliverable *procedure* with the function *to rank shipping company/company* has the function behaviors of *meet timing needs*, *meet client's needs*, and *meet the best criteria*. For both years, for the function *to rank shipping companies* approximately 15.0% of the student responses have the function description of *meet timing needs,* 5.0% and 2.7% were from Fall 2007 and Fall 2008 respectively for the function behavior *meet client's needs*, 4.5% in student responses were from Fall 2007 and 2.7% in student responses were from the latter year for the function behavior *to rank shipping companies/company*. There is no function description associated with the other deliverables.

Constraint. The constraint *based on data* exists only for the combinations: the structure *procedure,* with the function *to rank shipping companies*, and with the behavior *meet timing* needs, where 7.1% and 9.3% are from Fall 2007 and Fall 2008 respectively.

Table 3. Q2 – "In one or two sentences, what does the client need?" coding scheme for students' responses to Just-in-time manufacturing MEA.

Element and Related Codes	Code Descriptions	Sample Student's Response (responses are from both Fall 2007 and Fall 2008)
Structure – ***element of a complex system***		
Procedure	A written document such as a procedure, way, mathematical model, or method	*"The client needs the engineering team to design a* ***procedure*** [structure] *to* ***rank potential shipping companies*** [function] ***based on data collected*** [constraints]*,* ***in the order of most to least likely able to meet their shipping needs*** [function behavior]. *He also requires them to develop* ***a list of other factors besides timing that they beleive are important in the selection of a shipping company*** [constraints]*, and he requires all this before the end of the day."* (Figure 1, A)
Shipping company	Shipping companies involve in the shipments of materials	*"The company needs a* ***reliable*** [structural behavior] ***shipping company*** [structure] *so that they can* ***keep their production schedule and deliver the final product to their clients*** [function, counts are less than 10] ***on time*** [function behavior, counts are less than 10]. *"* (Figure 1, B)
Rank of shipping company	List or rank of shipping companies	*"The client needs a* ***ranking of the shipping companies*** [structure] *so that they can* ***decide which one is best for them to use*** [function, counts are less than 10]. *"*(Figure 1, C)

Element and Related Codes	Code Descriptions	Sample Student's Response (responses are from both Fall 2007 and Fall 2008)
Analysis of shipping data/company	Analysis of shipping data/company	*"The client needs a* ***strong*** [structural behavior – counts are less than 10] ***analysis of data*** [structure] to **find** [function – counts are less than 10] ***the best and most reliable*** [function behavior, counts are less than 10] ***shipping company****"*(Figure 1, D) *"The client needs us to* ***analyse eight different shipping companies*** [structure] ***and choose one of them*** [function – counts are less than 10] *on the bases of* ***statistical shipping data*** [constraints – counts are less than 10] *which can* ***ship the products on time*** [function behavior – counts are less than 10]*"*(Figure 1, D)
Others	No deliverable is indicated or cannot be coded in above categories	*"The client needs a* ***professional analytic opinion*** [structure] *as to* ***find a suitable shipping company*** [function – counts are less than 10] ***that will not delay in shipping products*** [function behavior – counts are less than 10]." (Figure 1, E)
Structure behavior – ***character/nature of the structure that enables it to achieve its function***		
Reliable/On-time/Meet timing needs	Shipping company that reliably delivers products on time	*"They need a* ***reliable*** [structural behavior] *shipping company* [structure] *that can* ***deliver their products to Alphalon on time***[structure behavior]**.** (Figure 1, B)
Structure function – ***the purpose of the structure that enables it to achieve its function***		
To rank shipping company	To rank shipping companies, goes with procedure deliverable	*"A* ***procedure*** [structure] ***to rank potential shipping companies*** [function]*."*(Figure 1, F)
To choose /find shipping company	To choose or find the best shipping company, goes with procedure deliverable	*"Client wants a* **procedure** [structure] ***to find the best shipping company for D. Dalton Technologies*** [function] *."* (Figure 1, G)
Function behavior – ***how the function behaves/acts***		
Meet some criteria for fast shipments	A description of a function to rank and to choose shipping company focused on the timing of shipments	*The client requires a* ***procedure*** [structure] ***to rank potential shipping companies*** [structure function] ***that can ship the materials for the manufacturing process on time*** [function behavior].(Figure 1, H) *"A* ***procedure*** [structure] ***to rank potential shipping companies*** [function] ***that will provide the most efficient, reliable, and fastest services*** [function behavior]." (Figure 1, H)
Meet client needs	A generic description of the function to rank and choose a shipping company focused on the client's needs	*"The client, DDT, needs a* ***procedure*** [structure] ***to determine which, of eight shipping companies*** [structure function]*,* ***can provide the best service for DDT*** [function behavior]*. Their previous shipping company was doing a poor job and shipments were arriving late. They need a new shipper and we are to give them direction on how to do so."* (Figure 1, I)
Constraint		
Based on data	Constraints on the function to rank shipping company	*"The client needs the engineering team to design a* ***procedure*** [structure] ***to rank potential shipping companies*** [function] ***based on data collected*** [constraint] ***, in the order of most to least likely able to meet their shipping needs*** [function behavior]*. He also requires them to develop a list of other factos besides timing that they beleive are important in the selection of a shipping company, and he requires all this before the end of the day."* (Figure 1, J)

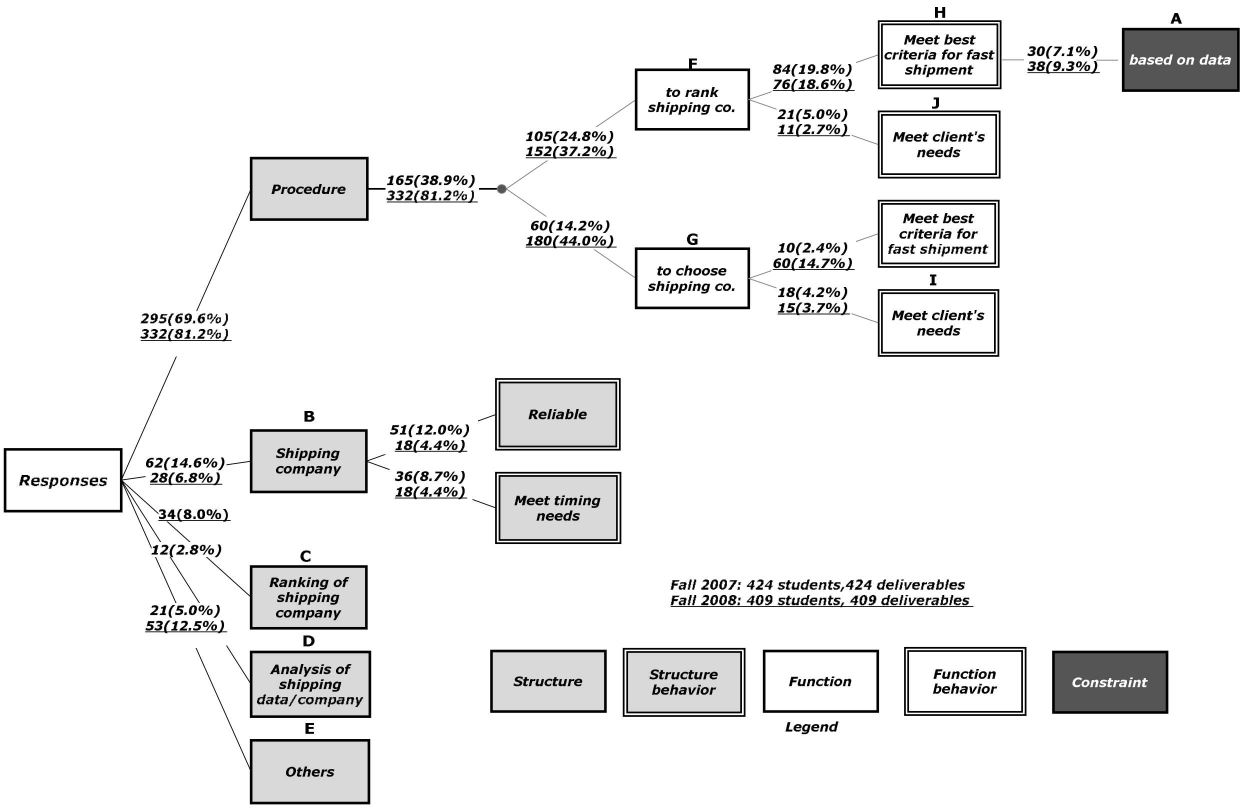

Figure 1: Descriptive node tree describing Q2 “In one or two sentences, what does the client need?” to *JITM* MEA.

3.3. Q3 – “Describe at least two issues …”.

Table 4 shows the codes for student responses to Q3, the code descriptions, and sample student responses for both Fall 2007 and Fall 2008. Table 5 and 6 list the percentages of students’ responses that are of each type issue, with Table 6 stating the increase or decrease in the percentages in Fall 2008 in comparison to Fall 2007. In Fall 2008, there are fewer students who restated the problem task (3.7%) in comparison to the previous year (8.3%). Students also provided more task-level issues in Fall 2008 (44.8%) in comparison to Fall 2007 (32.5%). Further, students provided more combinations of task- and context-level issues in Fall 2008 (27.8%) in comparison to Fall 2007 (7.8%). In Fall 2008, context-level issues represent only 8.1% of student responses, while in Fall 2007, context-level issues represent 32.1% of the student responses. Other categories are similar for both years.

Table 4. Q3 – "Describe at least two issues that need to be considered when developing a solution for the client" students' coded responses for *JITM* MEA,

Codes	Code Descriptions	Sample Student's Response (responses are from both Fall 2007 and Fall 2008)
Context-level-issues	Larger picture issues in relation to the problem context. This includes cost related issues, characteristics and quality of shipping company, history of shipping company, weather, and all other factors not related to delivery time issues, statistics, and other task-level issues.	*1) One of the issues to be considered is the safety record of the shipping companies, since the cargo is highly fragile material. 2) The other issue to be taken into consideration is the comparitive cost effectiveness of the companies, and the overall efficiency of its processes as a clue of its ability to deliver.*
		1. The cost of the shipment should also be considered. 2. The quality of the company (is the company reliable?) should also be considered.
		"Pricing of the service will be a factor. If you are spending too much on your service it will offset the profits of timely delivery."
		The weather conditions that the drivers are driving in need to be taken into consideration. The fact that the trend of the companies may change must also be taken into consideration, when choosing a company.
Task-level-issues	Task-level issues pertain to executable tasks to fulfil the procedure development. This includes statistics, shipping time-related issues, and data manipulation.	*"We need to find out what each company's average late time is as well as their maximum late time, and find a company that excels in both categories."*
		"What does the client mean by shorter amount of time. Is this mean by the average time is shorter or each one is constantly short amount of time. Does these datas similar through out the graph."
Restatement of the problem	Reiterating the problem description by questioning/restating the problem needed to be solved.	*"A second issue that we may face is communicating the procedure in a way that will allow it to be re-used in the future. A procedure that works only once will not truly solve the client's problem."*
		"1.include our team's reasoning for the each step 2.to develop a list of other factors besides timing"
		"A statistical analysis of the late times must be done."
		"First, that the client needs a reliable company ..."

Table 5. Q3 – "Describe at least two issues that need to be considered when developing a solution for the client" percentages of students' responses for Fall 2007.

Codes	Definition	Counts (Percentage out of *n = 468*)
Restatement of the problem	Restating task/reiterating requests from the problem text	*8.3%*
Task-level issues	Discussion around executable actions to rank shipping companies	*32.5%*
Context-level issues	Discussion around bigger context or logistics, such as cost, characteristics of shipping company, and weather	*32.1%*
Task and restatement of the problem	A combination of task-level issues and restatement of the problem	*14.3%*
Task and context-level	A combination of task-level and context-level issues	*7.8%*
Context-level and restatement of the	A combination of context-level issues and restatement of the problem	*2.1%*

problem		
Combination of all issue types	A combination of task-level issues, context-level issues and restatement of the problem	*1.9%*

Table 6. Q3 – "Describe at least two issues that need to be considered when developing a solution for the client" percentages of students' responses for Fall 2008.

Codes	Definition	Counts (Percentage from total *n = 482*)
Restatement-of -the-problem	*Restating task/reiterating requests from the problem text*	*3.7% (lower)*
Task-level issues	*Discussion around executable actions to rank shipping companies*	*44.8% (higher)*
Context-level issues	*Discussion around bigger context or logistics, such as cost, characteristics of shipping company, and weather*	*8.1% (lower)*
Task and restatement of the problem	*A combination of task-level issues and restatement of the problem*	*12.2%*
Task and context-level	*A combination of task-level and context-level issues*	*27.8% (higher)*
Context-level and restatement of the problem	*A combination of context-level issues and restatement of the problem*	*2.7%*
Combination of all issue types	*A combination of task-level issues, context-level issues and restatement of the problem*	*0.8%*

4. Discussion

In Fall 2007 there was no formal instruction on problem formulation, and GTAs received minimal training on problem formulation. In Fall 2008, there was a faculty-led lecture of problem formulation that focused on strategies for (1) identifying the direct client/direct user from amongst the stakeholders, (2) constructing a direct client/direct user's needs statement, and (3) engaging in problem scoping. The GTAs received professional development on problem formulation. This training focused on providing effective evaluation and assessment of student work, including responses to the individual questions. GTAs improved in their ability to grade and provide written feedback on the individual questions from Fall 2007 to Fall 2008 (Salim & Diefes-Dux, 2010; Ghazali & Diefes-Dux, 2012). In Fall 2008, prior to the *JITM* MEA, GTAs provided one round of feedback on students' responses to the individual questions for MEA 1 – Purdue Paper Airplane Challenge. Students could refer to and learn from this feedback when answering the individual questions for the *JITM* MEA.

Q1, *"Who is the client – the direct user of the procedure?"*,. To answer this question, students were required to think of the different stakeholders in the problem statement. For both Fall 2007 and Fall 2008, students were given essentially the same MEA context. However, for the second implementation, several minor changes were made to the MEA text. In Fall 2007, only indirect clients were described in the text (i.e. the DDT company and the CEO of DDT). However, in Fall 2008, a direct client/direct user was introduced - the Logistic Manager of DDT (see Appendix). Due to the fact that no direct client/direct user was in the Fall 2007 MEA text, students tended to identify indirect clients in response to Q1 at a rate of 87.0%. In contrast, in Fall 2008, only 31.0% of the student responses identified indirect users, while 57.5% of the student responses identified the direct user. There were also more multiple-client responses in Fall 2008, with three of the multiple-client categories being a combination that included the direct client/direct user. The greater percentage identification of the direct client/direct user in Fall

2008 may be attributed to the MEA text changes. However this percentage of the direct client/direct user responses is greater than that seen for either Fall 2007 MEA 1 (12.6%) or MEA 3 (10.8%) where neither MEA was missing the direct client/direct user in the text (Salim & Diefes-Dux, n.d.). So it is more likely that the formal instruction around Q1 and the GTA training has significant impact. Still, it was a concern that 42.5% of the student responses in Fall 2008 do not identify the direct client/direct user. We hypothesized that this may be due to the client language which was retained from the origins of MEAs for middle-school mathematics (Lesh, et al., 2000). We believe that the first-year engineering students associate the client term with entities that hire or supervise engineering teams rather than users of engineered products. In subsequent semesters, we have dropped the client language and focused on identifying direct users, indirect users, and non-users. This language is more consistent with the user-centered design terminology being used in the course during design thinking and learning activities.

For Q2, *"... what does the client need?"*. The anatomy of good response to problem identification to the MEA is similar to the structure-behavior-function (SBF) framework as described by Chan et al., (2010), where they utilize the SBF framework as an assessment metric in a biomedical engineering class. Cognitive scientists refer to structure as the "physical construction and elements" of a system, behavior as the "nature and how the physical construction and elements behave", and function as the "purpose of the physical construction and elements". In this work, the structure is an element which the client/direct user needs. The function describes the role and purpose of the structure, whereas the behavior describes how the function behaves to accomplish its function. The ability of a student to connect a structure to its function and behavior correlates positively and significantly to a student's performance in the biomedical engineering course (Chan et al., 2010).

The effect of formal instruction to Q2 can be seen by comparing students' response to both semesters. In the latter semester, more students provide the correct structure or deliverable, and connected the deliverable to its function. However, students from both years failed to connect the deliverable to its behavior, and the function to its behavior. In addition, students from both years did not provide constraints to their solutions. The results here are in alignment with the findings from previous studies where novice-like students lack the connection of a system to its function and behavior (Hmelo-Silver & Pfeffer, 2004). Hmelo-Silver & Pfeffer (2004) identified that novices focus on structures with minimal understanding of their behaviors and functions, while experts utilize functions and behaviors to organize their thinking and understanding of a system. Overall, the results here show that there is improvement in students' ability to identify the needs of client. These improvements may be related to the formal faculty-led lecture on the introduction to problem formulation and changes in the GTA training. However, we think that first-year students are still novices that lack an expert's ability; hence, the responses lack in-depth analysis and deep conceptual knowledge.

While some improvement is seen in student responses to Q2, it seems more careful instruction on problem formulation is needed. It may be that the mapping of the anatomy of a good response onto to the exemplar response to the sample MEA discussed by faculty in class may not be clear. Further, may not refer back to this example as a model for responding to Q2. Also, Ghazali and Diefes-Dux (2012) found that GTAs written feedback often did not address all of the elements of a good response when student responses were missing elements, particularly constraints. Both the introductory lecture material on problem formulation and GTA will need to be updated to better address student difficulties with Q2.

For Q3: *"Describe at least two issues that need to be considered when developing a solution for the client"*. In Fall 2008, students provided more task-level issues (44.8%) in comparison to Fall 2007 (32.5%). Students also associated more context issues with task-level issues in Fall 2008 (27.8%) in comparison to Fall 2007 (7.8%). In Fall 2008, students provided less context-level issues when only context-level issues were provided (8.1%) in comparison to 32.1% in Fall 2007. Categories of task-level issues or context-level issues with restatement-of-the-problem are similar in both years. However, students provide less restatement-of-the-problem issues in Fall 2008 (3.7%) in comparison to Fall 2007 (8.3%). Morozov, et al. (2007) identified that novices provide more social and natural factors which indicate a breadth-type approach to the problem. In other words, novices utilize their social framework in their solutions, rather than in-depth analysis of the problem.

In this study, we clearly see that students provided more context-level issues in Fall 2007, which pertains to social and natural factors familiar to the students, such as cost, weather, and quality of shipping products. Hence, we could say that both novices and experts have a tendency to bring in context into their solutions, with the latter bringing in richer context information grounded in deep conceptual knowledge. In Fall 2008, students provided more task-level issues, which are issues pertaining to statistical analysis (i.e., mean, median, range, standard deviation) and data analysis. This might indicate that students now responding to Q3 with ideas about how they are going to work with the data provided. In Fall 2008, students also bring in context when they provide task-level issues, indicating development of a trait of an expert at problem formulation – they make sense of the task at hand within the situated context details. Furthermore in Fall 2008, fewer students restated the problem; hence, students were more aware of the problem at hand and they are not just looking at the surface, but rather providing more in-depth analysis. This improvement in students' response to Q3 could indicate that students have better strategy for approaching problem scoping due to the formal instruction and the GTA training. Still, the phrasing of Q3 might be confusing some students, leading them to respond with context-level issues. This question has been reworked in a subsequent semester (Salim & Diefes-Dux, 2012).

5. Conclusion

The results of this study reveal that first-year engineering students do improve in their problem formulation ability in an open-ended probleming solving episode, such as a MEA when formal instruction on problem formulation is provided and GTAs are trained to provide effective grading and written feedback on student responses to guiding questions. A number of changes in the instruction on problem formulation have resulted (Salim & Diefes-Dux, 2012). These changes have also impacted the GTA professional development materials and face-to-face training. Future research will look into the impact these changes have on first-year engineering students problem formulation abilities.

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