Integrating Modeling Activities in Introductory Engineering Courses

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Abstract

This article argues for a future-oriented, inclusion of engineering modeling activities in introductory engineering courses at the university level. Engineering modeling activities provide a rich source of meaningful engineering problem situations that capitalise on and extend students' existing mathematics and engineering learning. We give consideration here to engineering modeling activities as a means for providing freshmen students with opportunities to work with authentic engineering problems even in introductory courses, to work in groups, to develop and revise powerful models and to document and present their solutions. We then report on a study in which a class of 29 first year civil engineering students developed several different models for solving the Bridge Design modeling activity. Results showed that students created models that adequately solved the engineering problem, although students did not seem fully aware of how their models should be revised in incorporating all provided data. Finally, recommendations for implementing engineering modeling activities and for further research are presented.

Introduction

Reform in engineering is being driven among others by The National Research Council's Board of Engineering Education and the Accreditation Board for Engineering and Technology Criteria for Accrediting Programs in Engineering (ABET, 2004). The National Research Council's Board of Engineering Education recommends ensuring "early exposure to engineering practice and a sense of the role of the engineer in society" (1995). In a traditional engineering education setting, engineering students often do not gain any experience solving complex problems that require teams of students until the third or forth year. With the increased pressure from industry and ABET to produce better prepared engineers, this traditional style of education needs to be updated. Engineering students, therefore, should have opportunities to work on multi-disciplinary teams and to apply mathematics and science when solving engineering problems (ABET, 2004).

One manner of addressing the calls for reform in Engineering and the introduction of problem solving skills in engineering programs, along with integrating teamwork and engineering contexts in the first years of engineering programs, is through the use of engineering model-eliciting activities (EngMEAs) – realistic, client-driven problems based on the theoretical framework of models and modeling (Lesh & Doerr, 2003). These activities are often introduced in a first and second year foundation engineering courses, and are being used as a vehicle for clarifying the nature of engineering and engineering practices to first-year engineering students, as well as demonstrating the usefulness of functioning on technical teams in realistic situations (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008; Zawojewski, Hjalmarson, Bowman, & Lesh, 2008).

Theoretical Framework

Current issues in engineering are often not seen by students until they are in their third and fourth year of undergraduate studies and sometimes only in elective or dual-degree graduate level courses. In recent years, there has been a push in engineering education to bring current advanced engineering topics to foundational courses. The purpose is to create interest in engineering as a career and to retain those already enrolled in engineering. Students engaged in advanced engineering topics early in their academic studies are more informed about the many disciplines of engineering and have a broader view of what engineering as a whole represents. Such students are likely to be interested in research at an early stage and are more likely to continue on into graduate studies in engineering. For these reasons, it is imperative that engineering educators consider methods for bringing advanced engineering content into foundational courses (National Academy of Sciences and National Academy of Engineering, 2007).

The National Academy of Engineering (2005) in the Educating the Engineer of 2020: Adapting Engineering Education to the New Century document provides engineering educators with direction to accomplish the mission raised above. The authors of the document propose that the growing need to look at engineering problems with a "systems perspective" drives the need to "pursue collaborations of multi-disciplinary teams of technical experts" (p. 10). The document further states that one of the important elements of engineering is the "engagement of the engineer and professional from different disciplines in team-based problem-solving processes" (National Academy of Engineering, 2005).

Model-eliciting activities (MEAs) are one method with which to teach modeling to undergraduate engineering students. A MEA is a complex problem solving problem set in a realistic context with a client, characteristics that place MEAs in the authentic assessment category (Lesh & Doerr, 2003). Solutions to MEAs are generalizable models which reveal the thought processes of the students. The models created include procedures for doing things and, more importantly, metaphors for seeing or interpreting things. The activities are such that student teams of three to four express their mathematical model, test it using sample data, and revise their procedure to meet the needs of their client (Mousoulides, Sriraman & Lesh, 2008).

The MEA framework provides a means not only to deliver more openended engineering problems (engineering content) but also address multiple ABET criteria, especially those that are problematic to integrate in engineering courses (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008). MEAs are accessible to first-year engineering students and they address ABET criteria and especially criterion 3 which requires that accredited engineering programs demonstrate that their graduates can meet standards such as an "ability to function on multi-disciplinary teams," an "ability to communicate effectively," and an "ability to identify, formulate, and solve engineering problems" (ABET, 2004), as in addition to eliciting models, MEAs require teamwork, design processes, and communication. In sum, from this models and modeling perspective, engineering-based problems are realistically complex situations where the problem solver engages in mathematical and engineering thinking beyond the usual introductory courses experience and where the products to be generated often include complex artifacts or conceptual tools (Lesh & Zawojewski, 2007). The problems present a future-oriented approach to learning, where students are given opportunities to elicit their own mathematical and scientific ideas as they interpret the problem and work towards its solution (Zawojewski et al., 2008).

The Present Study

Implementation of an Engineering Modeling Problem

In this section we report on first year civil engineering students' responses to an engineering modeling problem. The problem focuses on the 35W bridge that collapsed in Minnesota in 2007. Students explored properties and other characteristics of the four major types of bridges, as we present next. In implementing the problem, we were primarily interested in: (a) how the students interpreted the problem, (b) the ways in which the students worked with the data sets including how they selected, categorised, and operated on data, and (c) the nature of the models the students generated in solving the problem.

The Bridge Design problem was developed from an activity by Moore and her colleagues at the University of Minnesota. The problem entails: (a) a warm-up task comprising a newspaper article about the collapse of the 35W bridge in Minneapolis, designed to familiarize the students with the context of the engineering activity, (b) "readiness" questions to be answered about the article, and (c) the problem to be solved, including the tables of data. The data included both qualitative and quantitative information (see Table 1 and Table 2). The problem required students to use the data to develop a procedure to selecting the best possible bridge type for the reconstruction of the collapsed bridge.

Table 1: Four major types of bridges

Bridge Type	Advantages	Disadvantages	Span range	Material	Design effort
Truss bridge	-Strong and rigid framework -Work well with most applications	-Cannot be used in curves -expensive materials needed	Short to medium	Iron, steel, concrete	low
Arch bridge	-Aesthetic -Used for longer bridges with curves -Long life time	-Abutments are under compression -long span arches are most difficult to construct	Short to long	Stone, cast iron, timber, steel	low
Suspension bridge	-Light and flexible -Aesthetic	-Wind is always a concern -expensive to build	Long	Steel rope and concrete	medium
Cable-stayed bridge	-Cables are economical -Fast to build -Aesthetic	-Stability of cables need to be considered for long span bridges	Medium	Steel rope and concrete	medium

Participants and Procedures

One class of 29 first year civil engineering students worked on the problem as part of one of their introductory courses on integrated design. Since this problem was part of a sequence of modeling problems, students were familiar with working in groups, developing models for solving quite complex problems, and presenting and documenting their results. However, their completion of the present problem was the first time the students had the opportunity to work with engineering-based problems.

The problem was implemented by the authors. Working in groups of three to four, the students spent sixty minutes on the problem. During the first session students worked on the newspaper article and the readiness questions. In the next session students developed and documented their models. Finally, a class discussion followed that focused on the key ideas and relationships that the students had generated.

Data Sources and Analysis

Our data sources included audio- and video-tapes of the students' responses to the problem, together with their worksheets and the researchers' field notes. Specifically, the researchers videotaped the whole class discussions, and audiotaped each group of students. Using interpretative techniques (Miles & Huberman, 1994), the transcripts were reviewed by the researchers to identify and trace developments in the model creations of the students with respect to: (a) the ways in which the students interpreted and understood the problem, (b) their initial approaches to dealing with the data sets, and (c) the ways in which they selected and categorized the data sets, and applied mathematical operations in transforming the qualitative and quantitative data. In the next section we summarize the model creations of the student groups in solving the Bridge Design problem.

Table 2: Examples of four major types of bridges

Bridge Name	**Location**	**Bridge Type**	**Total length**	**Clear-ance below**	**Lanes**	**Construc-tability**	**Life time**	**Cost (Present value)**
Henne-pin Ave Bridge	Over Missis-sippi (Metro area)	Suspension bridge	1037 feet	37 feet	6	Easy	Fairly long (Build in 1990)	$100 million
10th Ave Bridge	Over Missis-sippi (Metro area)	Arch bridge	2175 feet	101 feet	4	Difficult	Long (Build in 1929)	$9 million
Green-way bridge	Hiawatha Ave, MN-55, Light Rail Line	Cable-stayed bridge	2,200 feet	20 to 27 feet	Bike and pedestri-an trials	Easy	Fairly long (Build in 2007)	$5.2 million
John E. athews Bridge	Florida, crosses St. Johns River	Truss bridge	7736 feet	152 feet	4	Difficult	Short (Build in 1953)	$ 65 million

Results

Group A Model Creations

Group A commenced the activity by discussing the four types of bridges presented in the first table (see Table 1). Students extensively discussed that it is important that the new bridge needs to be constructed very fast, since 35W motorway is one of the busiest roads in Minnesota. They also reported that Cable-stayed Bridge sounds as the optimal choice, since it is fast to be built and its only disadvantage is related to long span. They conclude (without any documentation) that the requested bridge span was medium and therefore there are not any problems in selecting the specific bridge type.

A second characteristic of Group's A work was the absence of any ranking or comparison between the four different bridge types. As a consequence, students in this group moved into the second table (the one providing examples of the different major types of bridges) and focused only on the two examples of Cable-stayed Bridges. However, they only discussed selected properties of the two bridges and did not focus their attention on all provided data. Specifically, students commented on the constructability factor, documenting that it is easy to construct Cable-stayed Bridges.

One student, however, disagreed with the others. He implicitly questioned the appropriateness of the specific type of bridge. He suggested incorporating into their discussion the bridge length and bridge life time. His suggestion has, however, a slight impact on the constructed model. Group did not use total length in any way; they only added that since life time for Cable-stayed Bridges was fairly long, this is the type of bridge appropriate for the Minnesota 35W Bridge. While students in this group used decision making processes for selecting the best possible bridge type, they did not provided any cost related models for comparing the different bridge types.

Group B Model Creations

Similar to the work of Group A, students in this group did not take into consideration all bridge types. They immediately excluded truss bridge, documenting that this was the type of the collapsed bridge and therefore people would not feel secured using the same type of bridge. They reported that: "It is better to use a new type of bridge. We should not be very concerned about the cost, but we will not use Cable-stayed Bridge or Suspension Bridge because it is too expensive". As a consequence, the students decided to choose the Arch Bridge. They documented that this type of bridge is quite cheap and can easily be used in the specific place; there are not any long span arches, and stone and concrete could be used.

While students reached the Arch Bridge type by excluding all other types of bridges, they failed and/or ignored to discuss the possible disadvantages of the specific type of bridge (e.g., the construction of the specific type of bridge is difficult (see Table 2). When prompted to further document and provide support for their choice, they reported that this is the only choice, considering that Truss Bridge can not be used and the other two types of bridges are too expensive. However, in their final letter, they also provided a second suggestion; they reported that a Cable-stayed bridge could be used if there are not any cost constrains, but without providing any further documentation. Finally, similar to Group's A work, they did not make any attempts to develop a cost model for comparing the different types of bridges.

Group C Model Creations

This group's work was similar to Group's A work in terms of selecting the Cable-stayed Bridge type, since according to the data provided in Table 1, this type of bridge can be constructed quite fast. In contrast to Group's A work, students in this group also did not comment on the design effort; they only reported that it is necessary to rebuild the collapsed bridge as soon as possible, since the 35W motorway is always too busy and many people use it everyday. In contrast to Group A, students in this group incorporated and discussed within their model other factors, like the design effort and the material used. This decision was not a straightforward process and students developed a ranking procedure for calculating the cost for each type of bridge.

While three students of the group supported from the beginning that the best possible bridge was the Cable-stayed Bridge, one student disagreed and prompted the others not to exclude suspension bridge type. He explained that: "Look at Golden Gate bridge. Do you remember that video (referring to a video they watched on the construction of the Golden Gate Bridge). Considering earthquakes, river water and really bad weather, this type of bridge is really great. Why not propose that type of bridge?" While the other three students commented that this type of bridge is too expensive, she proposed to develop a cost model for calculating the difference between the two types of bridge. During this discussion, the group finally decided to develop a cost model for all four types of bridges, although they made explicit that there was no possibility to propose the construction of a truss bridge type.

In their first attempt, students used a simple division model, dividing cost (at present value) by the total length of each bridge and then calculating the mean cost per bridge type. Almost immediately, students realized that the width of each bridge was not the same and therefore decided to develop a new model, based on a cost per ft2 of bridge deck. In developing this model, students faced difficulties in calculating the width of the different bridges. Using the Web, they found that the typical width of a lane was 12 feet and using this figure, they developed the cost per ft2 model presented in Figure 1. They also made an estimation of the width of bike and pedestrian bridges, by using in their model a fixed width (30 ft).

Figure 1: Group's C Cost per ft2 of Deck Model

D2 =B2*C2*12

	A	B	C	D	E	F
1	**Bridge Type**	**Length**	**Lanes**	**Total Deck Surface**	**Cost**	**Cost per ft2**
2	Suspension	1037	6	74664	100000000	1339,33
3	Suspension	8981	6	646632	212000000	327,85
4					**MEAN**	**833,59**
5	Arch	2175	4	104400	9000000	86,21
6	Arch	2100	30	63000	15000000	238,10
7					**MEAN**	**162,15**
8	Cable-stayed	2200	30	66000	5200000	78,79
9	Cable-stayed	13200	8	1267200	62000000	48,93
10					**MEAN**	**63,86**
11	Truss	7736	4	371328	65000000	175,05
12	Truss	2000	2	48000	2500000	52,08
13					**MEAN**	**113,57**

The students used this model to provide further validation to their initial selection and therefore they proposed that the best possible bridge type is the cable-stayed bridge. Quite surprisingly, students did not question at all their results, especially the big differences in their results within the same bridge type. The latter was among the additional information included in the model developed by Group D.

Group D Model Creations

Group D students started the problem by excluding Truss type Bridge. Students reported that they could not use the same bridge type. According to them: "Selecting the Truss type Bridge would make people feel insecure and bring back all those bad memories". Using the data provided in the first table, students concluded that all bridge types had their advantages and disadvantages and therefore they could not conclude from the first table on the recommended bridge type. Similar to Group's C work, they moved into the second table and decided to develop a cost model for ranking the different bridge types.

Group's D work was different from Group's C work in a number of dimensions. Although they also calculated the mean cost per ft2 of deck for each bridge type, they concluded that finding and comparing the means was not the best possible solution. They reported that: "Cost is not linearly proportional to length of the bridge and the level of difficulty in constructability is also a major factor. Further, comparing the means is not a good solution. For longer bridges the cost per ft2 is bigger than for shorter bridges". Students also approached the problem in a more sophisticated way; they considered the necessary extra lanes for bridges and bike and pedestrians lanes. They also incorporated into their model the difficulty level of each bridge construction, by dividing the final cost per ft2 by 1.5 for the bridges listed as "difficult constructability" in order to have the same basis of comparison for all types of bridges. Group's D final model is presented in Figure 2.

Students decided to compare similar bridges (approximately same length). These comparisons resulted in ranking the bridge types according to cost as follows: Arch, Truss, Cable-Stayed and Suspension Bridge. Students finally selected the Arch Bridge as the best possible solution for the collapsed bridge in Minnesota.

Figure 2: Group's D Cost per ft2 of Deck Model

	A	B	C	D	E	F	G	H	I
1	Bridge Type	Length	Lanes	Bikes	Extra Lanes	Total Deck Surface	Cost	Constructability	Cost per ft2
2	Suspension	1037	6	0	3	111996	100000000	Easy	892,89
3	Suspension	8981	6	0	3	969948	212000000	Difficult	145,71
4									
5	Arch	2175	4	0	2	156600	9000000	Difficult	38,31
6	Arch	2100	0	2	1	75600	15000000	Difficult	132,28
7									
8	Cable-stayed	2200	0	2	1	79200	5200000	Easy	65,66
9	Cable-stayed	13200	8	0	3	1742400	62000000	Easy	35,58
10									
11	Truss	7736	4	0	2	556992	65000000	Difficult	77,80
12	Truss	2000	2	0	1	72000	2500000	Difficult	23,15
13									

Remaining Groups' Model Creations

Students in these groups faced a number of difficulties in selecting and recommending a bridge type for the new 35W bridge. A number of groups focused their efforts on making qualitative comparisons between pairs of bridge types. As a consequence, some groups did not use at all the data provided in Table 2. Students faced a number of difficulties in working with both qualitative and quantitative data and their proposed solutions and models were not appropriate. Some students, for example, just reiterated each bridge type's characteristics as displayed in the tables of data, while others just ranked the four bridge types in their worksheets without any documentation of their method.

Discussion

In this paper we have argued that the inclusion of engineering modeling activities in the introductory engineering courses at a civil engineering course can engage students in creative and innovative real-world problem solving and can increase their awareness of the different aspects of problem solving in engineering. The problem we have implemented has been developed from a models and modeling perspective, which takes students beyond their usual problem-solving experiences to encounter situations that require substantial interpretation of the problem goal and associated complex data. Students have to elicit their own mathematical and engineering ideas and operations as they work the problem; this usually involves a cyclic process of interpreting the problem information, selecting relevant quantities, identifying operations that may lead to new quantities, and creating meaningful representations (Lesh & Doerr, 2003). Because students' final products embody the factors, relationships, and operations that they considered important in creating their model, powerful insights can be gained into the growth of their engineering thinking.

The students that participated in the present study developed a number of different models that adequately solved the problem, although not all models took into account all of the data provided. The students' models varied in the number of problem factors they took into consideration (cost per surface of deck, aesthetic of the different bridge types, design effort, constructability difficulty level, and length), with only one group developing a successful model considering both the engineering and the mathematical aspects of the problem. The groups also adopted different approaches to dealing with the problem factors. For example, some groups did not rank the different bridge types but only provided pair comparisons between the different bridge types, while some other groups developed quite sophisticated procedures for calculating the actual cost for each type of bridge and then ranked the four types.

Substantial more research is clearly needed in the design and implementation of engineering modeling activities in introductory engineering courses and the learning generated. We need to know, for example, (a) the developments in freshmen engineering students' learning in solving a range of engineering-based problems; (b) the ways in which the nature of engineering and engineering practice can best be made visible to these students; and (c) the types of engineering contexts that are meaningful, engaging, and inspiring for these learners.

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