Developing a Framework for Approaching Open-ended Problems Across the Civil and Environmental Engineering Curriculum

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Abstract

Year after year, we have found that our students struggle through their Capstone Senior Design Projects, with regards to how to properly define and approach problems, how to connect various components into one cohesive system, and how to apply and synthesize knowledge that they've acquired from their sub-discipline specific design courses. Additionally, as educators, we have struggled with providing students with the appropriate amount of information and guidance in helping students develop strategies for approaching and solving open-ended problems. To address this, we developed a framework that helps students (1) understand the relevance of content in lower-level civil engineering courses to real-life applications, (2) make connections through course content across civil engineering sub-disciplines, as well as non-engineering courses, and (3) understand impacts and create value in the broader, holistic perspective of their projects.

Additionally, we created a common project platform upon which to build and further develop project objectives in selected required technical design courses. This will facilitate the synthesis of all sub-discipline components to fit together as part of the overall system. The framework was introduced in the freshman introduction to design course with the intent for it to be revisited for specific course projects in the Civil and Environmental Engineering curriculum. The common course project platform was introduced in the freshman surveying course, where students collected geographical data. This project platform was revisited throughout the freshman year through the development of site plans and topographic maps of the project site in graphical communications and geographical information systems courses. This method provides a foundational context for a civil engineering site development that will be used in future courses for designing a multi-story building in a structural design course, analyzing soil samples for foundation design in a soil mechanics course, and developing a stormwater management plan in a water resources course.

To assess student learning, we created a site development scenario and asked students a series of questions about their problem-solving approach for creating a solution to the challenge presented. We developed a rubric for rating and comparing the responses. Students also rated their abilities for achieving learning objectives related to approaching open-ended problems. Thus far, we have baseline assessment results prior to full implementation of the developed framework and common course project platform.

Introduction

While engineers are problem solvers, studies demonstrate that engineering students lack the problem-solving skills expected after graduation [1, 2]. Problem-based learning (PBL) is a tool that allows an instructor to introduce problem-solving skills by organizing a course around a series of smaller, or one to two course-long problem(s) that add a substantial contextual element to class assignments and activities. Typically, the PBL approach integrates the theoretical side of education with the practical aspects of a profession, and involves students in not just the solving of the problem, but also the investigating, developing, explaining, and checking of solutions [3, 4]. This pedagogical approach has long been used in medical education, and has more recently emerged as an important approach for the undergraduate classroom [4]. Emphasizing the investigating and developing aspects of the PBL approach, open-ended problem (OEP)-based learning has roots in the constructivist developmental theory where students can piece their experiences of the world together to construct their understanding of the world [5]. An OEP approach focuses on allowing students to apply their own approaches in solving problems and has been implemented in mathematics education [6]. An OEP approach intends to shift learning responsibility to students; an instructor's role is to guide and support discussion and evaluation of strengths and weakness of resolutions to the problems [6].

Application of OEP in two upper-level mechanical and aerospace engineering courses found that students struggle both cognitively and affectively when presented with OEP. Specifically, for the cognitive domain, students demonstrated difficulty in defining problems, applying first principles, making assumptions, and self-assessing their problem-solving skills. For the affective domain, students demonstrated difficulty in spending time on task, sketching and taking notes during their problem-solving process, and being comfortable with ambiguity [6].

At Rose-Hulman Institute of Technology (RHIT), we have witnessed our students struggling through their capstone projects in terms of defining and approaching the problem, connecting various components into one cohesive system, and applying and synthesizing knowledge from sub-discipline specific design courses to create a complete design. We were able to observe these weaknesses because of the nature of our year-long capstone design course. In the winter quarter, students from different design teams are organized into technical subdisciplines for the detailed technical design portion of the capstone design experience [7]. The exact break down of the technical subdisciplines depends on the nature of the team's project. For example, for a four-person team, one team member might join the structural engineering technical design course, one person might join the water resources engineering technical design course, one person might join the geotechnical engineering technical design course, and one person might join the transportation engineering technical design course. Each technical subdiscipline has between five and 10 students taught by at least two faculty. This high student to faculty ratio has allowed us to observe these weaknesses over the course of a 10-week term, over years of teaching design.

While we have observed these weaknesses, as educators, we have struggled with providing students with the appropriate amount of guidance in the process of developing strategies for approaching comprehensive problem-solving. To address these issues, we developed a two-pronged approach using OEP-based strategies: implementation of a common project platform that students will develop and solve throughout their undergraduate civil engineering experience, and implementation of a framework to help students scaffold ambiguous problems so that they can tackle them appropriately and with confidence.

In the current civil and environmental engineering curricula at RHIT students are exposed to PBL and OEP instructional approaches in various classes (Table 1) to varying degrees. All students take a freshman design class in the spring term of their freshman year, and a year-long capstone design course in their senior year. Otherwise, students take classes that may or may not include projects, which are more or less open-ended, depending on the instructor and the year.

Table 1: Courses with projects currently in the civil and environmental engineering curriculum

Academic Level	Course Name	Brief Description of Course Project
Freshman	*Introduction to Design*	Students design a site layout.
Sophomore	*Mechanics of Materials*	Students design and construct a balsa wood bridge truss.
	Sustainable Design	Students conceptually design an aspect of a high performance building.
Junior	*Hydraulic Engineering*	Students design a water distribution system.
	Water Resources Engineering	Students create a rainfall-runoff model and design infrastructure to manage stormwater.
	Concrete Design	Students design reinforced concrete members for a building.
Senior	*Senior Design*	Students complete a capstone design project.

Methods

In order to help our students make a connection between theory and real-life application, two approaches were implemented to improve student's ability to solve open-ended problems: (a) A Framework to Approach Open-ended Problems and (b) A Common Project Platform for Synthesizing Components of Open-ended Problems.

<u>Framework for Open-ended Problems (OEP)</u>
Based on our interaction with students during their capstone design projects and course projects in some of our required courses, we realized students had a difficult time to even approach OEPs: specifically, where do they find resources, how do they make connections to knowledge obtained in previous courses, what appropriate assumptions do they make, what are the constraints, how do they even know whether the solution makes sense, etc. Hence, to provide

some guidance, we established a framework that outlines key steps to solving open-ended problems. It's our goal that this framework will be utilized by students in our project-based learning courses that are an integral part of our common project platform. This framework is based on the *Wood's Problem-Solving Methodology* [1]. A methodology that was successfully implemented and assessed in some key mechanical engineering courses at San Jose State University [8]. Below is a brief description of each step for our framework:

Step 1- Define
In this step, students define the project needs and the relevance of the project in a larger context. This include the identification of relevant stakeholders, design requirements and constraints.

Step 2 – Plan
The next step requires the students to perform a desk study on the existing conditions of the site. This includes but not limited to identification of potential impacts of the project, creation of a site plan to include topography, boundary conditions etc. This will require some research on the part of the students.

Step 3- Create and Evaluate
Students develop a breath of appropriate design options through an iterative process. Additionally, students will establish a set of criteria by which these options will be evaluated to select the optimal option that meets the stakeholders needs. Through this iterative process the students critical thinking skills can be evaluated and assessed.

Step 4- Design
After selecting an optimal design option, students undertake a complete technical design of the project, including a cost estimate of the proposed design. Additionally, issues related to constructability are also addressed at this stage.

Step 5- Reflect
In final step of the framework, the students evaluate the effectiveness of the design process in meeting the stakeholder's expectations. Most importantly, students will be required to discuss lessons learned, challenges faced and future considerations with regards to appropriate solution to the project.

Table 2 provides a summary of the utilization of the framework in some of the required courses in the civil engineering curriculum. The framework will be utilized in its entirety in the freshman introduction to design course (EM103) and the senior design course (capstone projects). For all other required courses, the extent of utilization of the framework will depend on the objectives of the course project. For example, in the structural mechanics course (i.e. CE321), "*Step 4*" of the framework will be emphasized since the course project involves the analysis and design of a multi-story building.

Additionally, the freshman courses, *CE101*, *EM102* and *CE111* do not make use of the framework, however, they do form an integral part of the common project platform by providing data used to create the site plan for the common project platform.

This problem-solving methodology will be implemented in the freshman design course to ensure familiarization of the design process by the students early on in their college education. Additionally, to help students' better approach their senior design projects, the design steps in the framework mimics key project deliverables in the capstone design course.

A summary of the implementation of the common platform projects as well as utilization of the framework in the civil engineering curriculum is also shown in Table 2.

Table 2: Implementation of the common platform projects and utilization of the framework in the civil and environmental engineering curriculum

Course Description	Common Project Platform	Utilization of the Framework
Freshman Courses		
CE101-Engineering Surveying	Survey potential area for the project.	
EM102-Graphical Communications	Use AutoCAD to create a site plan.	
CE111- Geographic Information Systems	Use GIS to create a site plan.	
EM103-Introduction to Design		Introduce framework
Sophomore Courses		
EM203-Mechanics of Materials		Utilize framework with deeper learning of Step 3
CE250-Sustainable Civil Eng.	Conceptual design of high performance building techniques.	Utilize framework with deeper learning of Steps 1 & 2
CE380-Introduction to Transportation Eng.	Roadway/intersection design for the project.	
Junior Courses		
CE321-Structural Mechanics	Structural analysis of a multi-story building.	Utilize framework with deeper learning of Step 4
CE336- Soil Mechanics	Soil sampling and analysis	
CE371-Hydraulic Eng.	Water distribution system for the project.	Utilize framework with deeper learning of Steps 4 & 5
CE471-Water Resource Eng.	Stormwater management plan for the project.	Utilize framework with deeper learning of Steps 4 & 5
CE441- Construction Eng.	Create a work schedule for the project.	
CE432-Concrete Design	Design of reinforced concrete members.	Utilize framework with deeper learning of Step 4
Senior Courses		
CE450-Civil Eng. Codes and Regulations	Erosion & Sediment control plan for the project.	
CE486-489-Senior Design		Utilize entire framework

Common Project Platform

As previously discussed, the common project platform was implemented to facilitate the synthesis of all sub-discipline components as part of the overall system. A meeting was scheduled with all the course instructors involved in order to establish a project platform that will meet their course objectives. The goal for this meeting was to ascertain from the course instructors if such a project could be undertaken without major changes to their course syllabus. Additionally, the course instructors selected, already had a project component as part of their course requirements. Hence, we did not encounter any bureaucratic hurdles prior to implementation of the platform.

Table 3 shows the sequence in which the common project platform will be implemented. Beginning in the freshman year, students will gather data that will be used to create a site plan for the project. In the subsequent years, students will work on various aspects of the project as part of the course requirements in the various civil engineering sub-disciplines. For example, in the fall of the junior year, the students will work on different aspects on the project in the *Hydraulic Engineering*, *Structural Mechanics* and *Soil Mechanics* courses. Working on different aspects of the project in the same quarter will help students understand how the civil engineering sub-disciplines fit together in a project.

Table 3: Touchpoints for the implementation of the common project platform and framework

Freshman			**Sophomore**			**Junior**			**Senior**		
Fall	*Winter*	*Spring*	*Fall*	*Winter*	*Spring*	*Fall*	*Winter*	*Spring*	*Fall*	*Winter*	*Spring*
[P]CE101	[P]CE111			[F]EM203	[P]CE380	[PF]CE371	[PF]CE471		[P]CE450		
	[P]CE102	[F]EM103		[PF]CE250		[PF]CE321	[PF]CE432		[F]CE486	[F]CE487	[F]CE489
						[P]CE336	[P]CE441				

[P]Indicates courses that are part of the *Common Project Platform*.
[F]Indicates courses that implement the *Framework*.
[PF]Indicates courses that are part of the *Common Project Platform* and implement the *Framework*.

Results and Discussion

In order to assess learning over the four-year curriculum, we performed surveys at the start of freshman year and end of senior year. Through the surveys, students rated their abilities for achieving learning objectives related to approaching open-ended problems. The baseline data are from a first-year cohort and a fourth-year cohort from the 2017-18 academic year. The data show how perceptions may change in a general sense from freshman to senior year, but this particular data set does not track changes for one cohort over time.

Students rated their level of agreement/disagreement with each statement based on their perceived ability to achieve each learning objective (Table 4). The response options were: 1=Strongly Disagree, 2=Disagree, 3=Slightly Disagree, 4=Neutral, 5=Slightly Agree, 6=Agree, 7=Strongly Agree.

Table 4: Student responses of ability to achieve OEP learning objective

	Start of Freshman Year: 2017-18 (n =32)		End of Senior Year: 2017-18 (n =30)	
	Mean	Standard Deviation	Mean	Standard Deviation
I am able to identify perspectives of various stakeholders by viewing project in context of larger society.	4.41	1.64	5.63	1.38
I am able to synthesize knowledge from sub-discipline specific design courses to recognize interdependence.	4.38	1.66	5.47	1.31
I am able to integrate content from all courses across curriculum to develop meaning in context of holistic perspective.	4.97	1.47	5.33	1.40
I am able to apply systems thinking to real-life complex problems to achieve desired outcome	4.94	1.72	5.47	1.31
I am able to evaluate technical feasibility, societal benefits, environmental impacts, and economic viability.	5.88	0.91	5.33	1.52

When comparing student perceptions of their ability to achieve OEP learning objectives, there was no statistically significant difference between responses from the 2017-18 freshman cohort and the 2017-18 senior cohort. This shows that within the existing curriculum, without implementation of particular learning touchpoints for addressing open-ended problems, student confidence of achieving these objectives does not change. This finding reinforces the need for implementation of an approach to help students address open-endedness in problem solving throughout the curriculum.

Additionally, we created a site development scenario and asked students a series of questions about their problem-solving approach for creating a solution to the challenge presented. We also wanted to isolate the capstone senior design experience, so students were surveyed at the start of senior year, in addition to the start of freshman year and end of senior year.

Students were presented with the following scenario: *Last year, a community purchased a new building and an 18 acre tract. The community would like some assistance in determining how to best utilize this property. The design team is required to create a layout design for this land development project to include a couple of soccer fields, picnic pavilion, softball diamond, concessions building, parking, etc.*

Students then responded to the following questions:

1. *How confident are you with your ability to solve this problem?*
2. *Identify reasons why you feel confident or lacking in confidence (i.e. level of technical expertise, accepted problem solving approach/method, level of real life experience, level of personal contribution to a team effort).*
3. *What information is missing that would help you better understand this problem statement?*
4. *What data are needed to solve this problem?*
5. *What CE subdisciplines are involved and how?*
6. *Would you need expertise from other disciplines to solve the problem? If so, what other disciplines?*
7. *What information would be needed from an expert in other disciplines?*
8. *What stakeholders are involved?*
9. *How will your project affect each stakeholder?*
10. *How might this project affect the local community and larger society?*
11. *What are potential positive benefits and negative impacts of this project on society?*
12. *What information do you need to determine if this project is financially feasible and economically viable?*
13. *How might this project affect the environment, locally and globally?*
14. *What are potential positive benefits and negative impacts of this project on the environment?*
15. *In one sentence, briefly describe the final components of the conceptual design.*
16. *How would you determine if this is technically feasible?*
17. *In one sentence, describe how these components interact as a whole system.*
18. *In what other ways can this problem be solved? Identify one alternative conceptual design or different components of the conceptual design.*

To assess survey responses, we developed a rubric for rating and comparing the responses. For each question, a range of anticipated student responses was used to establish targeted categories, some of which were distinctive groupings, while others were thresholds along a spectrum of substantive description in a response. The rubric will be used to code the responses and categorize the collection of responses for each question to illustrate the distribution and track any changes to the distribution of responses over time.

Conclusions

As we continue to see students struggle with their approach to addressing open-ended problems, we anticipate that our two-fold strategy of the framework combined with a common project platform will help students view their project from a more holistic perspective and synthesize the various subdiscipline components into one whole system. We are currently implementing our approach in the freshman year. As our staged implementation approach continues through the four-year curriculum, we will reflect upon the successes and difficulties that we undergo as we help our students be better equipped to face real-world engineering challenges.

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