AC 2012-4469: LEVERAGING SIMULATION TOOLS TO DELIVER ILL-STRUCTURED PROBLEMS IN STATICS AND MECHANICS OF MATERIALS

Prof. Christopher Papadopoulos, University of Puerto Rico, Mayaguez

Christopher Papadopoulos is an Assistant Professor in the Department of General Engineering at the University of Puerto Rico, Mayaguez. He earned B.S. degrees in civil engineering and mathematics from Carnegie Mellon University (1993) and a Ph.D. in theoretical and applied mechanics at Cornell University (1999). Prior to coming to UPRM, Papadopoulos served on the faculty in the Department of Civil Engineering and Mechanics at the University of Wisconsin, Milwaukee.

Papadopoulos has primary research and teaching interests in mechanics, including nonlinear structural analysis, computational mechanics, and biomechanics. He is also active in engineering education and engineering ethics, particularly in the subjects of mechanics education and appropriate technology. At UPRM Papadopoulos serves as the coordinator of the Engineering Mechanics Committee in the Department of General Engineering. He also co-coordinates the Social, Ethical, and Global Issues (SEGI) in Engineering Program and Forums on Philosophy, Engineering, and Technology.

Dr. Aidsa I. Santiago-Romn, University of Puerto Rico, Mayaguez

Aidsa I. Santiago-Romn is an Assistant Professor in the Department of Engineering Science and Materials and the Director of the Strategic Engineering Education Development (SEED) Office at the University of Puerto Rico, Mayaguez (UPRM). Santiago earned a B.A. (1996) and M.S. (2000) in industrial engineering from UPRM, and a Ph.D. (2009) in engineering education from Purdue University. Her primary research interest is investigating students’ understanding of difficult concepts in engineering science with underrepresented populations. She also teaches introductory engineering courses such as problem solving and computer programming, statics, and mechanics.

Dr. Genock Portela-Gauthier, University of Puerto Rico, Mayaguez

Genock Portela is an Assistant Professor in the Department of General Engineering at the University of Puerto Rico, Mayaguez. He earned a Ph.D. degree in structural engineering at the University of Puerto Rico, Mayaguez (2004). Portela has primary research and teaching interests in structural mechanics, mostly oriented to bridge, earthquake, and wind engineering. In the General Engineering Department at UPRM, Portela serves as President of the Planning and Development Committee and Member of the Engineering Mechanics Committee.

Rosaurelis Marn Ramirez, University of Puerto Rico, Mayaguez

Rosaurelis Marn Ramirez is a sophomore in Industrial Engineering at the University of Puerto Rico, Mayaguez. Rosaurelis is currently employed as an undergraduate research assistant in Engineering Education, conducting investigation related to the Concept Assessment Tool for Statics and Schema Training. She will likely continue her graduate studies and work in the area of Statistics, Reliability and/or Optimization. Her ultimate goal is to make a difference in the world by contributing positively to society.

Paola Pacheco Roldan, University of Puerto Rico, Mayaguez

Paola Pacheco Roldan is a sophomore in Industrial Engineering at the University of Puerto Rico, Mayaguez. Paola is currently employed as an undergraduate research assistant in Engineering Education, conducting investigation related to the Concept Assessment Tool for Statics and Schema Training. She is interested in Statistics and hopes to pursue graduate studies, ultimately seeking to positively impact society.
NSF Poster:
Leveraging Simulation Tools to Deliver Ill-Structured Problems:
Enhancing Student Problem-Solving Ability in Statics and Mechanics of Materials

1. Introduction

This poster is based on the NSF TUES Project “Leveraging Simulation Tools to Deliver Ill-Structured Problems: Enhancing Student Problem-Solving Ability in Statics and Mechanics of Materials” (#1044866) that was awarded to the University of Puerto Rico, Mayagüez. A decision was made to re-title the project as “Simulation and Ill-Structured Problems in Mechanics to Leverage Engineering Expertise, or SIMPLE2”.

Engineers and non-engineers alike widely characterize engineering as a discipline whose purpose is to “solve problems”, and this is often framed as “design”\(^1\). Despite movements since at least the 1990’s to reform engineering education to integrate design throughout the curriculum, including during the freshman year, engineering curricula remain dominated by “linear” and “top down” models that postpone the introduction of design. In this standard model, basic math and science (“analysis”) courses are given during the first two years, followed by application of this knowledge to conduct basic engineering analysis during the second and third years, and culminating in engineering design (e.g., capstone design projects) during the last year\(^2,3\). The inherent premise underlying this curricular structure is that engineering design ability will naturally follow from this linear sequence of knowledge-building activities.

Among many problematic artifacts of this traditional pedagogy is the dominance of well-structured “textbook” problems, i.e., idealized, artificial, narrowly-focused, analysis-based problems in which exactly the requisite assumptions are provided for a given situation that already represents a working design, and for which the solutions require only “forward” analysis and/or “plugging in” numbers into formulae. The inherent premise underlying this overreliance on well-structured problems is that enough practice with them (presumably over a sufficient range of topics) will adequately prepare students to solve “real” problems, which are, of course, ill-structured, particularly in engineering design. However, leading scholars and educators challenge this premise. According to learning theorists Jonassen et al.\(^4\),

> “Educators historically have assumed that learning to solve well-structured problems positively transfers to solving ill-structured workplace problems. However, recent research has shown that learning to solve well-structured problems does not readily transfer to ill-structured problems.”

Several engineering educators corroborate this, observing that even when students demonstrate mastery of rote skills, they have difficulty transferring these skills to interpretive and ill-structured contexts\(^5,6\). More generally, leading proponents of integrating design into
engineering education recognize the direct link between “design” and “ill-structured” and/or “open-ended” problems\textsuperscript{7,8,9}.

In the basic mechanics courses, well-structured problems are further limited to using hand calculation, in which a previously derived formula can often be used uncritically. An example of such a problem would be to determine the deflection of a point on beam, using the “standard linear theory”, given the beam’s length, cross-sectional dimensions, elastic modulus, and boundary conditions.

There are two principal shortcomings of this approach. First, such problems avoid engaging students in design or design-oriented thinking. Real engineering design problems, after all, can have multiple solutions and often require some thinking on the part of the engineer to evaluate and develop some underlying assumptions. In general, problems of this nature are termed “ill-structured”. A large body of engineering education literature has convincingly demonstrated the benefits of introducing design or design-oriented thinking at early stages of the curriculum.

The second major shortcoming of this approach is that it restricts the students’ thinking to only ideal problems that have analytical solutions and which can be completed by hand calculation (possibly with the aid of a calculator). Real engineering design problems, of course, do not always admit pure analytical solutions, and even when the do admit (in part) such solutions, the volume of calculation required would make hand calculation impractical. While hand calculation problems remain necessary to illustrate fundamental behaviors and concepts, limitation to only such problems retards students’ preparation to solve modern engineering problems, and postpones their exposure to the very simulation tools that they will eventually use later in their careers. Indeed, the recent ASEE Report \textit{Creating a Culture for Scholarly and Systematic Innovation in Engineering Education}\textsuperscript{10} advocates “the introduction of … technologies … into new or existing learning environments and their continued improvement”.

In this project we seek to address these twin shortcomings by developing new modules that deliver ill-structured mechanics problems that include, at least in part, the use of simulation tools such as finite element analysis software. An extensive literature review undertaken as part of the project’s preparation revealed that such an integrated approach is rare, and has certainly not been developed in any systematic manner. This review is summarized in the Appendix. For practical considerations, the scope of this project is limited to developing such modules for the courses Statics and Introductory Mechanics of Materials, and in anticipation of subsequent Civil Engineering courses in Advanced Mechanics of Materials and Structural Analysis. A rigorous educational research component is included to measure both immediate and longitudinal impacts of the modules.

2. Pedagogical Philosophy and Module Development

As noted above, a major shortcoming of the tradition engineering curriculum is its linear, top-down nature. This curriculum can be represented by the following diagram:
Many educational theorists have argued that employing feedback loops can accelerate student learning. Inspired by these ideas, we suggest that the curricular model can be reformed to include both “forward looking” and “backward looking” elements, as suggested in the following diagram:

In this process, not only is design included at early stages, but its usual position at the end of the curriculum is anticipated by specific elements that occur earlier. Similarly, in later courses, specific elements can be included to strategically revisit fundamental concepts from prior courses. To make this concrete, consider the following example:

In traditional Statics, students are asked to determine the forces in members of an ideal, weightless truss. But in fact, students could be asked to consider how these forces change if their lengths or angles are changed, and including the effect of member weight. This anticipates realistic design problems that would occur in subsequent advanced courses.

What can make this process work from a practical standpoint is the appropriate incorporation of simulation tools that enables students to consider such system variations efficiently. Following the ideas of Papadopoulos et al.\textsuperscript{11}, the modules will be designed to employ these tools as “sophisticated calculator” in which students will be able to direct system or parameter variations and obtain meaningful output that is understandable (it is the task of this project to create “pre-built” modules that can be easily manipulated by students). In contrast to approaches such as Brinson et al.\textsuperscript{12}, the modules will not attempt to engage students in theoretical derivations of the theory that underlies the simulation tools.

An initial presentation of this approach to some colleagues elicited some concerns. These concerns and our responses are summarized in Table 1.
<table>
<thead>
<tr>
<th>Objection</th>
<th>Response</th>
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<tbody>
<tr>
<td>Students must first learn mechanics, then learn FEA theory, and then apply FEA to design problems</td>
<td>A linear pedagogy is not necessarily best, and has many limiting aspects</td>
</tr>
<tr>
<td>Teaching FEA or other simulation tools in courses like statics will take time away from the core theory</td>
<td>We will develop tools, such as GUI’s, that will enable students to operate simulation tools more simply; this will manage the time spent on learning tools. Another point is that software tools are becoming more and more user friendly, and it is possible to ask students to learn the basics to operate them. Also, in many cases, the simulation will be deliberately invoked to repeat a calculation done by hand, thus reinforcing theoretical concepts.</td>
</tr>
<tr>
<td>Students will not be able to maturely operate simulation tools and interpret results</td>
<td>True in general, but the project will design modules to manage this process and guide students use and interpretation. In particular, they will be exposed to “validation &amp; verification” by making comparisons with hand calculations.</td>
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After having this discussion, some colleagues became more inclined to at least give it a cautious chance. This lead to a discussion of what the project could positively contribute. One such idea revolved around the use of classical formulae in design classes. The point was made that many students misuse formulae from prior courses by applying them to circumstances in which they are not valid; in other cases students do not apply or incorrectly apply formulae in instances when they can be used. An example of this type was the use of the shear stress formulae “VQ/It” for transversely loaded beams. This expression is applicable only to certain points of the beam cross section, but students often apply it at points where it is invalid. A consensus was reached that simulation could help students learn when to use, and when not to use, various formulae.

To robustly identify both appropriate topics and modes of delivery, a panel of approximately 20 experts is being assembled to participate in a Delphi. A Delphi process is one in which a set of experts is assembled and queried to make predictions or offer suggestions to address an issue, moderated by a facilitator, and has the following basic stages:

1. Exploration: participants contribute additional information pertinent to the issue or discussion;
2. Assessment: points of agreement/disagreement and meanings of relative terms such as importance, desirability, or feasibility are identified;
3. Understanding: underlying reasons for significant disagreements or divergence are identified and evaluated;
4. Final Evaluation: final recommendations are synthesized and fed back for consideration.

A detailed summary of the Delphi process for this project is included in Appendix 2.

3. Educational Research Strategy

Motivated by Froyd et al.\textsuperscript{14}, this project seeks to measure cognitive gains resulting from our interventions (modules), both in the immediate class during which are modules are delivered, and later points in subsequent courses. To facilitate this longitudinal measurement, we devised a “curricular strand” (see Table 2), which is a set of four consecutive courses: INGE 3031 Statics, INGE 4011 Mechanics of Materials I, INGE 4012 Mechanics of Materials II, and INCI 4021 Structural Analysis. The modules will serve as “interventions” in the first two of these courses, and immediate learning outcomes will be measured at the end of these courses. No new interventions will be introduced to the last two courses, but impacts from the first two courses will be measured in these courses.

<table>
<thead>
<tr>
<th>Table 2. Schematic of Curricular Strand.</th>
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<tbody>
<tr>
<td><strong>INGE 3031 Statics</strong></td>
</tr>
<tr>
<td>Prior Interventions: None</td>
</tr>
<tr>
<td>New Interventions: Statics Modules</td>
</tr>
<tr>
<td>Immediate Outcomes: Statics Modules</td>
</tr>
<tr>
<td>Long Term Outcomes: None</td>
</tr>
</tbody>
</table>

As outlined in Table 2, the use of the curricular strand allows for assessment of both “immediate” and “long term” learning outcomes. “Immediate” outcomes are those that result of an intervention is delivered, e.g. a survey or post-test at the end of the semester. “Long term” outcomes are those that result from interventions that occurred in prior courses.

The assessment instruments developed in this project will be designed to answer the following fundamental research questions:
(1) Are simulation tools effective for the delivery of ill-structured problems?  
(2) Do students engaged in solving ill-structured problems (according to our framework) show gains in learning and problem-solving ability?

In particular, we will attempt to develop instruments that measure problem-solving ability by measuring declarative, conceptual, and procedural knowledge (though not necessarily in strict sequence). These types of knowledge will inform the design of the modules. A detailed description of the research protocol is in Appendix 3.

3. Sample Module: Beam-Column

In general the modules will address both Core and Exploratory material. Core material relates to traditional analytical course content, whereas Exploratory material relates to broader ideas such as results of varying model parameters or exposure to future topics. The modules will also contain a mixture of Well-structured (WS) and Ill-structured (IS) problems.

We provide a sample module based on concepts of equilibrium, internal force and stress, and displacement in the context of a beam supported by a cable. Note that this example illustrates integration of ideas between Statics (INGE 3011), Mechanics of Materials I (INGE 4011), Mechanics of Materials II (INGE 4012), and Structural Analysis I (INCI 4021). Many variations of this problem can be created to span the range of Core and Exploratory material, as well as WS and IS.

For example, the module can be initiated in Statics (INGE 3031) is the starting point, implementing Problem 1-a as one of the type WS. The problem provides the following data: (i) magnitude and location of the concentrated load; (ii) dimensions of the beam and the cable; and (iii) boundary conditions. The student will be asked to answer the following questions

- What is the magnitude and orientation of the reactions?  
- What is the magnitude and direction of internal forces in the beam?  
- What is the magnitude and direction of internal forces in the cable?

Problem 1-a (Figure 3) shows the product obtained by the computer program for the internal forces. The student will have the opportunity to associate their findings with the program, compare and identify the errors. It is important to mention that the student does not have to know the use of the computer program. The project team will provide an easy to use template to assist the student in his or her investigation.

The same problem will be transformed to one of the IS type, changing the position and angle β in the cable (Problem 1-b, Figure 3). This case enters as part of the Core material of INGE 3031. The student will be asked to answer the following questions

- What effect is produced in the reactions?  
- What effect is produced in the internal forces of the beam?  
- What effect is produced in the internal forces of the cable?
As an example, these effects are seen using the computer program results, as shown in Figures 1-a and 1-b. The student will distinguish how changes in geometry, in this case represented by the increase in the angle $\beta$, produce an increase in the reactions and the internal forces of the system (Figures 1-a and 1-b). Note that shear in the beam undergoes an increase in the order of 5 times and the flexural moment in the order of 3 times due to changes in the $\beta$ angle.

While the course presents methods of analysis, it is also introducing design concepts implicit in it. The student will understand the importance of taking into account the geometry of the systems to perform an efficient design. The instructor will provide and show the students the graphic results obtained with the program.

Problems 1-a and 1-b can be extended to study issues related to deformation and stress in the elements of the hinged frame (1-c and 1-d). These subjects can be introduced in INGE 3031 as Exploratory, while they are included in the course INGE 4011 as Core. Sample questions could be as follows:

- What elements experience axial stress?
- What elements experience shear stress?
- What is the effect produced in the stress of the beam and the stress of the cable when you change the position and angle $\beta$ in the cable?
- What is the effect produced in the stress of the beam and the cable when we increase the area of the elements by a factor of 2?
- What effect is produced in the stress of the elements when we increase the inertia of them by a factor of 2?

The answers to these questions can be presented and discussed as shown in the Problem 1-c and Problem 1-d (Figure 4):

![Figure 3. Internal forces: (a) WS problem and (b) IS](image)

![Figure 4. Graphical representations of deformations and stress values (from SAP2000).](image)
Bibliography


Appendix 1: Details of Literature Review

As per our focus, we conducted a reasonably exhaustive search to identify prior efforts to incorporate “design” and/or “open-ended” and/or “ill-structured/defined” problems into “Statics” and/or “Mechanics of Materials” (alt. “Strength of Materials”), relying primarily on the indices from the Journal of Engineering Education and the ASEE Conference Proceedings (dating since 1993 and 1996, respectively). Over 70 sources emerged from this search, from which we identified a subset of 22 “Exemplary Projects (EP)”, listed below, in which students were specifically tasked with solving problems that were design-oriented and not well-structured. For clarity, examples of projects excluded from the EP subset are those that are purely demonstrative, such as enhanced visualization tools or experimental apparatus that demonstrate common phenomena (though we do not suggest that such efforts are without value or merit).

Some key findings of the 22 projects in the EP subset are as follows:

- the vast majority (17) engaged students in a single, several-week or semester-long design project (e.g. designing and/or building a bridge); only 4 provided a set of shorter length problems or modules [Rencis et al., 2005; Wood et al., 2002; Guarino & Cahill, 1998; Brinson et al., 1997] (the remaining 1 was ambiguous);
- somewhat more than half (13) required the students to perform some type of numerical computation or simulation;
- all 22 identified the need to expose students to “design”; the vast majority (17) identified the need to engage students in solving “open-ended” problems, but only 2 specifically identified engagement with “ill-structured” or “ill-defined” problems;
- nearly a quarter (5) developed projects that connected Statics and Mechanics of Materials, often through developing combined Statics-Mechanics of Materials courses;
- while reported assessment results were generally positive, only 3 projects included assessment beyond student evaluations/surveys or faculty observation [Esche & Hadim, 2002; Woods et al., 2002; Guarino & Cahill, 1998]; only 1 developed a controlled experiment to demonstrate learning gains [Wood et al., 2002];
- none of the projects attempted to measure skills transferred beyond the immediate course in which the project was undertaken.

In summary, although there have been several prior efforts to cultivate “open-ended” problem-solving ability in mechanics (under the broader umbrella of “design”), very few have linked such problem-solving with simulation, and nearly none have demonstrated rigorous assessment results.

Exemplary Projects (EP)


Appendix 2: Delphi Process

**Phase 1: Panel Selection.** A group of 20-25 expert participants will be selected, consistent with Clayton’s rule of thumb\textsuperscript{A1}. Experts will be selected from tenured and tenure-track engineering professors from research universities and undergraduate institutions whose primary teaching responsibilities are in engineering mechanics and structural analysis. A general solicitation for participants will be distributed through the ASEE Mechanics and Civil Engineering Divisions, and redundantly, individual announcements will be extended to colleagues identified by the PI’s, such as available authors of texts in Statics and Mechanics of Materials. For purposes of diversity, efforts will be made to include women and faculty from other Hispanic-serving institutions.

**Phase 2: Concept Exploration.** We will first ask the experts, through open-ended response, to identify topics/themes in Statics and Mechanics of Materials around which they would recommend the creation of special modules. In providing their input, participants will be asked to consider concepts that pose difficulty to students, usefulness throughout the strand, and feasibility of development of simulation tools. Responses will be coded by the investigators and the research assistants to develop a list of topics identified by at least two panelists. This list of concepts will form the basis for our subsequent phases. All responses from Phase 2 will be held confidential.

**Phase 3: Concept Ranking.** A questionnaire will be developed based on the topics generated in Phase 2. Each expert will be asked to rate each concept based on two factors (each time using a scale from 1-10 that we will provide: (1) how important it is for a student to have competency in the topic, and (2) what proportion of students have competency in the topic. The questionnaire will be provided in web-based and Word document format. Responses from Phase 3 will be held confidential.

**Phase 4: Panel Consensus.** After tabulating the results from Phase 3, the same questionnaire (again in both web and Word formats) will be redistributed to the panelists (same topics, same ranking scales) but with the following additional information provided: the median response and middle 2-quartile range of responses for each question from Phase 3. Panelists will be asked to re-rank the topics. Panelists who at this point choose a ranking that lies outside of the 2-quartile range established in Phase 3 will be asked to provide an explanation for their rating. We expect
that the median ranking of each concept will approach a stable value (the interquartile range will decrease), leading toward a consensus opinion. Responses from Phase 4 will be held confidentially.

**Phase 5: Final Selection.** We will ask experts to make a final ranking of concepts identified in Phase 2, with the median ratings and the anonymous comments justifying out-of-range rankings from Phase 4 provided. Based on this final iteration, the most common and most important topics will be selected to develop the instructional modules and accompanying questions.

**Appendix 3: Research Design**

**Theoretical Framework.** The researchers will use grounded theory, a method of qualitative inquiry designed to generate an explanatory theory of a specific process or phenomenon. Grounded theory is an inductive approach in which theory is derived from the data through a process of asking questions and making comparisons. The primary objective is to expand on an explanation of a phenomenon by identifying the key elements and the relationships among them within the specific context of the research study. Thus, in this study, a grounded theory approach will enable the researchers to develop a theoretical account of the characteristics of expert problem solving while simultaneously grounding it in empirical data.

**Cohort Building.** During the Spring 2011 enrollment period, we will recruit 50 Civil Engineering (CE) majors who will be enrolling in Statics for Fall 2011 to form our first experimental cohort (typically 150 CE majors overall enroll in Statics each Fall). The cohort will be selected so that the average and distribution of student academic and gender characteristics match the profile of the remaining CE students not in the cohort.

Once selected, students will be formally invited to join the experimental cohort. They will receive a summary of the project goals (i.e. the use of modules to solve ill-structured problems) as well as a description of the curricular strand that begins with Statics and ends with Structural Analysis. Students will be asked to accept the invitation to join the cohort with the understanding that they will be expected to continue for at least three consecutive semesters (through Mechanics of Materials II, which is required of all CE majors); this includes their commitment to take all corresponding prerequisites, which we will explicitly list. Students who fail in one of the courses in the strand will be removed from the cohort.

Assuming usual student progress and choice of student concentration, we anticipate 35 students remaining in the cohort to begin Mechanics of Materials I (Spring 2012), 25 to begin Mechanics of Materials II (Fall 2012), and 15 to begin Structural Analysis (Spring 2013).

A second cohort will be formed by similar means. The second cohort will begin Statics during Fall 2012 and reach Structural Analysis by Spring 2014. The reason for waiting until Fall 2012 to begin the second cohort (and not Spring 2012) is because we will be studying various formative assessment feedback during Summer 2012 and make appropriate revisions for Fall
2012. Note also that since Spring 2014 is beyond the last scheduled semester of funding, results from this last semester (Structural Analysis) will be analyzed after the project completion date (c.f. a similar note in Section 2.4).

**Delivery of Instruction to the Cohort.** The planned interventions of this project – the new course modules – will be delivered in Statics and Mechanics of Materials I. To ensure proper and reasonably uniform delivery of these modules, all students in the experimental cohort will be taught in the same designated course sections by one of the investigators (Papadopoulos or Portela). Note that during Mechanics of Materials I, as a result of attrition in the cohort, it is possible that some students who are not in the cohort will be enrolled in the same section with students in the cohort. In such cases, these students will receive the same course instruction (i.e. modules). Further details of the delivery of the modules are provided in Section 5.

For the Mechanics of Materials II and Structural Analysis, we plan no further interventions, and correspondingly, we do not attempt to congregate students of the cohort into common designated sections. Likewise, it is very possible that students in the cohort will receive instruction an instructor who is not one of the investigators. Nevertheless, students in the cohort will continue to recognize their participation in the project through regular communications that they will receive from us, including interviews and think-aloud’s that will be part of the research process.

Our methods will also be informed by wisdom from the literature. Woods et al.\(^5\) pointed out the inability of isolated ill-structured/open-ended problems to foster general problem-solving ability without also providing a supporting metacognitive framework, in which activities such as workshops and journaling help students become aware that they are engaged in solving ill-structured (and by extension, cognitively challenging) problems. They also recommend developing ill-structured problems in gradual stages from simple to more complex. Wood et al.\(^6\) noted that instructor attitude also has a large bearing on the influence of an instructional method. They report that in their efforts to deliver open-ended problems, the results depended on the level with which the instructor believed in the approach in the first place. With these ideas in mind, in our delivery of the modules, an identity will be created among the cohort through written materials, occasional group events, and metacognitive questions attached to the modules themselves. Moreover, two of us (Papadopoulos and Portela) will be the primary instructors who will deliver the modules in Statics and Mechanics of Materials in order to ensure similar quality of instruction in the experimental cohort.

**Measures of Logistical Facility.** We will measure the success of the delivery of the modules by establishing a questionnaire given to student in the cohort during Statics and Mechanics of Materials I. These questions will focus on student impressions of the use of simulation tools, e.g., are they able to learn how to use the tools sufficiently to student topics in mechanics, or are the tools themselves difficult to use and distracting. In addition, the research assistants, who will also serve as teaching assistants for the designated course sections, will collect data regarding the types of questions and difficulties that students have regarding the logistical use of the tools required in each module.
Cognitive Measures. Several methods will be employed to measure cognitive performance of students in the experimental cohort. We plan to conduct the following processes to collect data.

- **Standard Exams Questions.** The Engineering Mechanics Committee chair (Papadopoulou) will coordinate the delivery of common exam questions for all sections of Statics and Mechanics of Materials I. These questions will likely be of usual well-structured format that test basic analytical problem-solving. Student performance on these questions will be compared between the experimental cohort and control group. In Mechanics of Materials II and Structural Analysis, in which we anticipate mixture of cohort and non-cohort students in the same section, we will compare basic student performance, e.g., exam scores and final grades, between the experimental cohort and control group members.

- **Concept Assessment Tool for Statics (CATS).** Because the modules will be used, in part, to develop student understanding of concepts, we will administer the CATS to all Statics students both as a pre- and post-test. We will then compare performance based on absolute post-test scores and normalized gain between the experimental cohort and the control group.

- **Think-alouds.** Each semester, we will select approximately 10 students from the experimental cohort and 10 from the control group to solve various types of ill-structured in a think-aloud process. Participants will be instructed to read aloud the case problem and to think aloud as they work on the problem, telling everything they are thinking from the time the problem, until finished. Retrospective interviewing will occur immediately after the think-aloud to help participants reflect on and verbalize their thought processes during the think-aloud, drawing from both long-term and short-term memory (e.g., “Describe the process you used to think about the case”). In addition, interviews will include questions to clarify comments participants made during the process and to explicate how knowledge and experiences were used. Transcriptions will be examined using a constant comparison method, with specific attention given to participants’ references to prior knowledge and experiences. Initially, each researcher will conduct an analysis of a single transcription, looking for evidence related to our two research questions but without establishing preconceived ideas about what might be discovered. A set of tentative profiles that captured each participant's response to the case situation will be generated. Following this, two researchers will apply a modified open-coding process using an electronic copy of each transcription, inserting comments and highlighting quotes that seem particularly relevant to our questions. However, rather than create a set of categories and subcategories as is typical in open coding, we will create a set of themes that reflects each participant's responses. Themes for each participant will be shared and discussed between the two researchers as they will be developed. After identifying the themes, we will identify common similarities to create a set of assertions that could be applied to the majority, if not all, of the participants. If a theme is not evident among at least four participants, it will not be
used in the final set of assertions. Finally, after the assertions are developed, they will be presented to the rest of the research team (with evidence) for additional comment and final team verification. The team will then work together to find relevant supporting or contradictory evidence from the literature.

Additional References Cited from Appendices


