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Leveraging Simulation Tools to Deliver Ill-Structured Problems in Statics and Mechanics of Materials: Initial Results

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1. Introduction

This paper reports initial results after the first semester of implementation of a TUES project during the Fall 2012 semester at the University of Puerto Rico Mayagüez (UPRM). This project introduces new modules in Statics and the subsequent course of Mechanics of Materials that are designed to accomplish the following three goals simultaneously:

- Accelerate development of student design expertise
- Develop simulation competency
- Advance use of longitudinal assessment to determine efficacy

We seek to accomplish these goals by introducing ill-structured problems into the Statics and Mechanics of Materials courses. By "ill-structured" we mean problems that require students to evaluate or provide assumptions, investigate appropriate background information, compare several "what if" scenarios, or otherwise perform design or design-related tasks. Such problems differ in at least some manner from "well-structured" problems that are typified by textbook problems that provide students with all of the requisite information and only this information, that possess unique solutions, and which can be done on pencil & paper.

Engineering design problems are by nature ill-structured, but the curriculum remains dominated by courses and textbooks that feed students a steady diet of well-structured problems. Whether engineering educators consciously believe that expertise in well-structured "building block" problems automatically translates into expertise in ill-structured (design) problems is perhaps an open question, but several leading education researchers challenge this assumption and argue that direct experience with ill-structured problems throughout the curriculum is necessary in order to build expertise in activities such as engineering design[1-6]. We further note that ill-structured problems provide opportunities for students to anticipate topics from subsequent courses and allow for smooth vertical integration; we adopt this approach here.

The incorporation of simulation tools is important for its own sake and as reviewed in Papadopoulos et al. has several prior precedents[7]. But use of simulation tools can amplify the effectiveness of ill-structured engineering problems, particularly when a design question requires several computations that are either tedious or too numerous to effectively do by hand. We further believe that simulation tools can be meaningfully introduced to entry level students in a manner that does not require them to understand the underlying computational theory of the tool, but in a manner that can enable them to interpret results more maturely[8].

We note that the target cohort of this study is students in the Civil Engineering degree program. A reason for selecting a specific cohort is so we can track student progress longitudinally along a "curricular strand", which is a set of consecutive courses within a major. Although our interventions will take place only in Statics and Mechanics of Materials I, we will measure student progress in the subsequent courses Mechanics of Materials II and Structural Analysis to assess the lasting effectiveness of our approach.

2. Description of New Course Modules

Several experts both at our institution and at others were polled as to what types of issues and problems are important to address in the mechanics courses for students in the Civil Engineering/Structural Engineering track. Based on their responses and on practical issues, we developed three new modules, summarized as follows:

- **Module 1: Slope of Road**. In this module, assigned during Week 1, students were asked to determine the slope of a road on campus that is considered steep. This was designed to serve as a review of basic trigonometry and to introduce students to an ill-structured problem in which they were left to determine the methodology and how to interpret their results correctly. We viewed that prior knowledge of students was sufficient to undertake this modules with a minimum of explanation. A photo of the road is shown in Figure 1.

Figure 1. Photo of Road for Module 1.

- **Module 2: Redundant Three-bar Structure**. In this module, which was assigned in Week 6 (after a basic introduction to force equilibrium), students were provided with the problem of a weight hanging from a joint at which are joined three truss members (2-dimensional system), as shown in Figure 2.

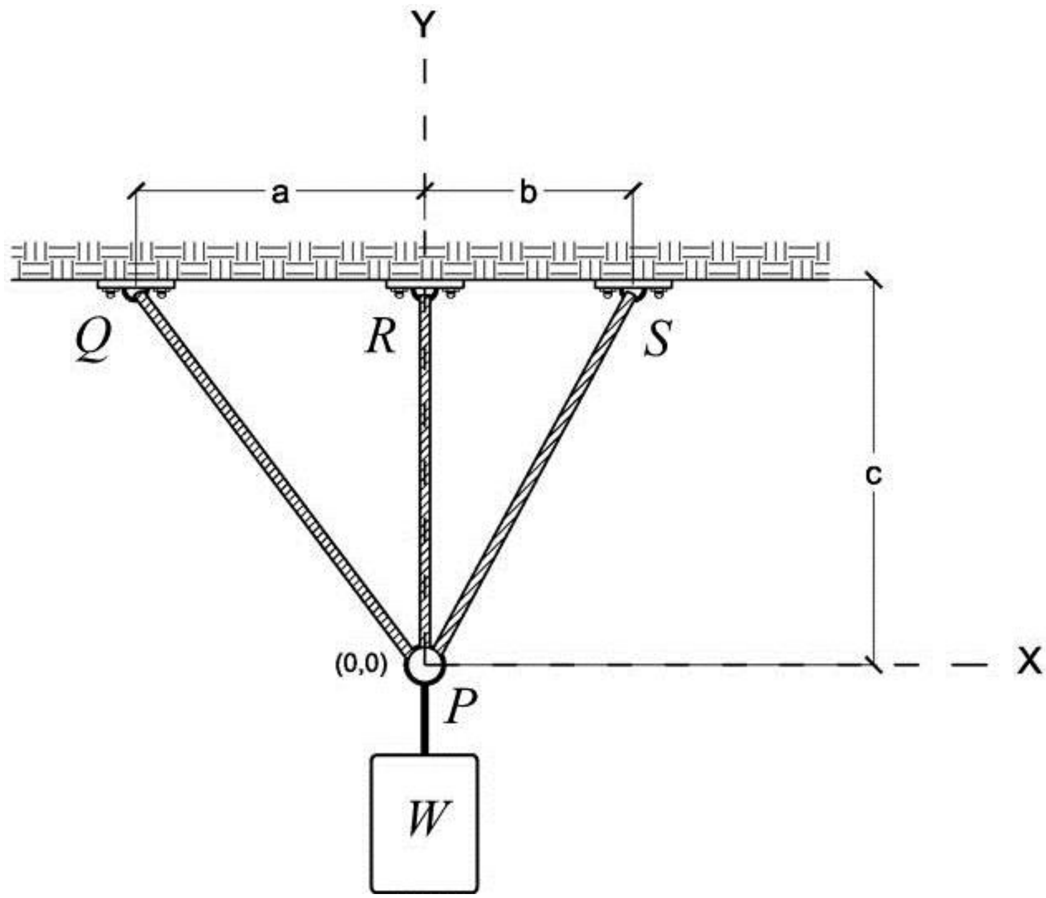

Figure 2. Sketch of Three-bar Redundant Truss

At its basic level, this module required students to look up the elastic modulus of the given material, determine the displacement of the joint, and determine the force carried by each member. At is deeper level, students were asked to investigate changes in these behaviors based on changes in geometry and material.

Such a problem is usually not presented in a statics course because the topics of elasticity, displacement, and redundancy are presented in Mechanics of Materials. However, under our approach, we provided the students with a tutorial that provided the equations of compatibility and translated the typical bar stiffness *EA/L* into and equivalent spring stiffness *k*, which is familiar to Statics students. Students were then asked to enter parameters into a prepared Excel Spreadsheet that would enable them to solve for the displacement of the joint and subsequently the forced in each member. Figure 3 shows an annotated image of the spreadsheet that students can use to solve the problem.

Parameters

	10^3 ksi		in		in
E_PQ	29.0	d_PQ	0.50	a	16.00
E_PR	29.0	d_PR	0.50	b	12.00
E_PS	29.0	d_PS	0.50	c	12.00
	k/in		deg		in
k_PQ	284.7	θ_PQ	143.1	L_PQ	20.00
k_PR	474.5	θ_PR	90.0	L_PR	12.00
k_PS	335.5	θ_PS	45.0	L_PS	16.97

Equation Table

	δ_PQ	δ_PR	δ_PS	δ_x	δ_y	load
Sum Fx	-227.8	0.0	237.3	0.000	0.000	0.00
Sum Fy	170.8	474.5	237.3	0.000	0.000	5.00
C1	1.00	0.00	0.00	-0.800	0.600	0.00
C2	0.00	1.00	0.00	0.000	1.000	0.00
C3	0.00	0.00	1.00	0.707	0.707	0.00

Results

F_PQ	1.288
F_PR	3.197
F_PS	1.457
δ_PQ	0.0045
δ_PR	0.0067
δ_PS	0.0043
δ_x	0.0006
δ_y	-0.0067

Figure 3. Spreadsheet corresponding to Module 2. Students enter parameter values at the top and then enter coefficients into a matrix that will solve the equilibrium and compatibility equations. Green = manual entry of given data; Yellow = calculated value from a given formula; Red = research or interpretation required; Gray = automatic output. Green-Red fade: manual entry becomes interpretive when doing a 'what if' scenario in which students need to vary parameters in order to understand trends in system behavior.

- **Module 3: Design of a Steel Signpost.** In this module, which was assigned in Week 12 (after students had completed the study of rigid body static equilibrium in 3 dimensions), students were asked to investigate how to determine the size – particularly the inner and outer diameters – of a steel signpost that supports a billboard, within given limits of size and allowable stress. The other geometric dimensions (height of sign, width of sign, etc.) were given, as were estimates of loads due to weight and wind. Figure 4 illustrates the basic model. Again, such a problem is beyond the traditional statics curriculum because it requires at least basic analysis of stress at the base of the post. But under our approach, we provided the students with a simple tutorial introducing the concept of stresses (due to axial, bending, lateral shear, and torsion), and a prepared spreadsheet that calculated the required stresses at the base.

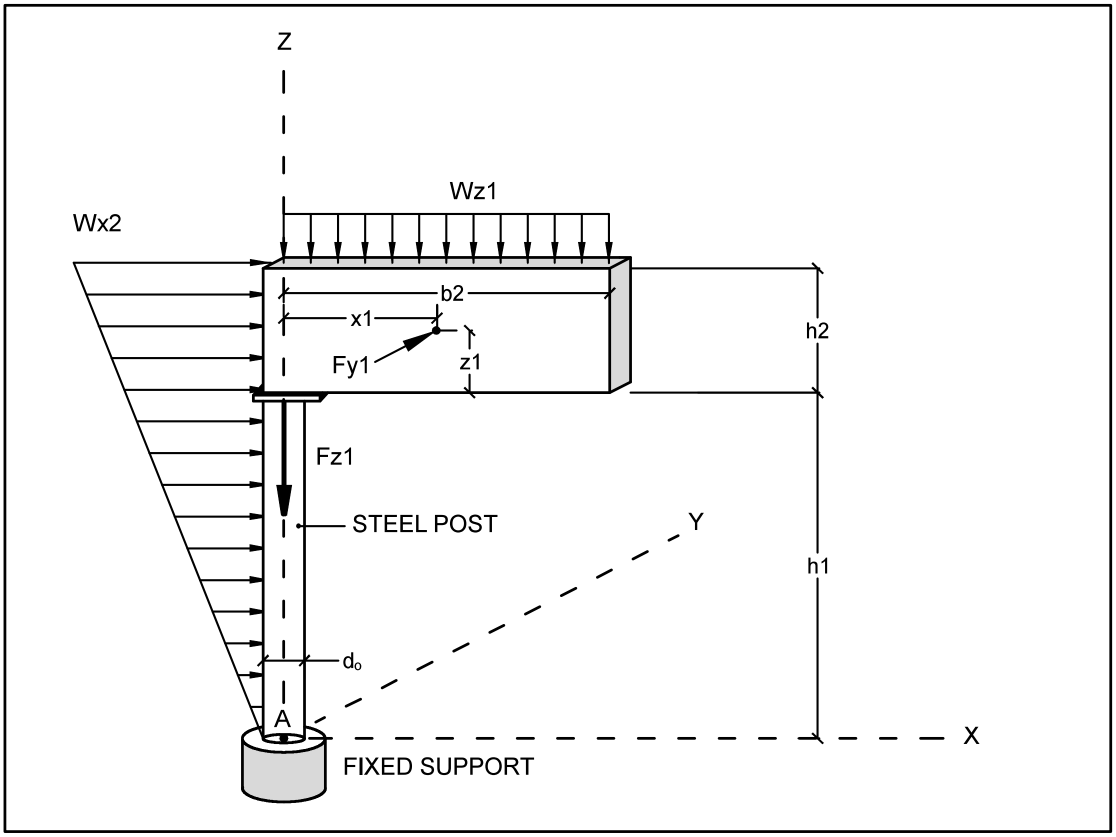

Figure 4. Illustration of Signpost and Billboard for Module 3.

Students were asked to first determine the reactions at the base of the signpost (by both including and excluding the weight of the signpost itself) using completely traditional static equilibrium equations. These reactions were then to be entered or directly calculated in specific cells within the prepared Excel spreadsheet. Students could then enter test values of inner and outer diameter of the post. Once the reactions and trial dimensions were entered, four stress quantities were automatically calculated: normal stress due to axial load; normal stress due to bending; shear stress due to lateral force; and shear stress due to torsion. By comparing the resulting stresses with allowable limits, students were asked to recommend a size of the pole. However, they are also asked to consider whether any other factors, such as size or weight, would also influence their choice of design. Additional questions were asked to probe their understanding, such as why a solid post is not used, why it is (apparently) sufficient to study stress at the base of the pole an nowhere else, and which load(s) is (are) most influential in driving the design (including, in particular, whether the weight of the post itself is significant in this sense). Figure 5 shows an annotated image of the spreadsheet that student can use for Module 3.

						wind x	wind y	wt sign			
Param	**x1**	**z1**	**b2**	**h1**	**h2**	**Wx2**	**Fy1**	**Wz1**	**γ Steel**		
Units	**ft**	**ft**	**ft**	**ft**	**ft**	**k/ft**	**k**	**k/ft**	**k/ft^3**		
Value	**6**	**4**	**13**	**28**	**8**	**0.70**	**8.00**	**0.90**	**0.49**		
Units	in	in	in	in	in	k/in	n/a	k/in	k/in^3		
Value	72	48	156	336	96	0.0583	n/a	0.0750	0.00028		
Reactions	**Vx = Ax**	**Vy = Ay**	**Vresult**	**P = Az**	**Mx**	**My**	**Mresult**	**T = Mz**			
Units	kip	kip	kip	kip	kip*in	kip*in	kip*in	kip*in			
Value	-12.6	-8.00	14.93	11.70	3072	-4541	5483	-576			
Property	d_o	d_i	**t**	**A**	**Ix**	**J**	**c**	**Wt Post**			
Units	in.	in.	in.	in.^{2}	in.^{4}	in.^{4}	in.	kip			
Value	**28.25**	**27.50**	**0.375**	32.84	3190	6380	14.13	**4.02**			
Stress	σ_{axial}	σ_{bend}	**max** σ_z	**Allow**	Summary	d_o	d_i	**t**	**max** σ_z	**max** τ	**Wt Post**
Units	ksi	ksi	**ksi**	ksi		in.	in.	in.	ksi	ksi	kip
Value	0.36	24.28	**24.63**	25	Hollow1	34.25	33.75	0.250	24.77	2.40	3.27
Stress	$\tau_{lateral}$	$\tau_{torsion}$	**max** τ	**Allow**	Hollow2	28.25	27.50	0.375	24.63	2.18	4.02
Units	ksi	ksi	**ksi**	ksi	Hollow3	24.75	23.75	0.500	24.53	2.06	4.67
Value	0.91	1.28	**2.18**	16	Hollow4	22.50	21.00	0.625	24.83	1.99	5.20
					Solid	14.25	0.00	7.125	24.23	1.26	19.54

Figure 5. Spreadsheet corresponding to Module 3. Students enter parameter values, then calculate reactions at the base, then enter trial values for inner and outer diameter, then read stresses at the base. Green = manual entry of given data; Yellow = calculated value from a given formula; Red = research or interpretation required; Gray = automatic output. Green-Red fade: manual entry becomes interpretive when doing a 'what if' scenario in which students need to vary parameters to understand trends in system behavior. Gray-Red fade: reading automatic output becomes interpretive when selecting a design.

Table 1 summarizes the content and attributes of the three modules.

Table 1. Content and attributes of the three modules introduced in Statics during Fall 2012.

Module Title	**Weeks**	**Traditional Statics Topics**	**Mechanics of Materials Topics Integrated**	**Simulation Tool Required**	**Ill-structured Attributes**
1. Slope of Road	1-2	Trigonometry	None	None	Select methodology of determining slope; correctly verify or interpret answer; recognize or comment on possible errors in method
2. Redundant Structure	6-8	Force Equilibrium of Particle	Axial displacement; use of approximations to compute displacements; analysis of redundant structure	Excel Spreadsheet	Look up E for steel and aluminum; estimate for bungee cord; correctly sense order of magnitude of solution; vary parameters in spreadsheet to see system behavior
3. Steel Signpost	13-16	Force and moment reactions in 3D, including as caused by distributed loads	Stress analysis; failure stress and factor of safety	Excel Spreadsheet	Look up unit weight of steel; vary parameters in spreadsheet to see system behavior; iterative use of spreadsheet to arrive at design.

3. Initial Results from Fall 2012 Statics Intervention

The three new course modules were delivered in three sections of Statics, two taught by one of the authors, and one taught by another of the authors. At total of 146 students were enrolled, with 49 being in the target population of Civil Engineering. Table 2 provides a summary of the pre-course profile and performance data of the students.

Table 2. Profile and Performance of Statics Students in Targeted Sections, Fall 2012.

Cohort	N	Avg GPA prior to Fall 2012 semester Max = 4	Avg grade in Calculus I: first attempt Max = 4	Avg Grade in Statics Fall 2012 Max = 4	Avg Grade in Module Statics Fall 2012 Max = 10	Avg Score on CATS post test Fall 2012 Max = 27 (number of takers)	Received C or higher in Statics Fall 2012 AND passed Calculus II prior to Spring 2013	Enrolled in Target Section of MoM I Spring 2013
All	146	2.75	1.24	1.51	6.64	8.72 (89)	n/a	n/a
Civil Eng	49	2.68	0.92	1.22	6.68	8.47 (30)	15	7
Mech Eng	38	3.03	1.84	2.16	6.95	10.39 (28)	n/a	n/a
Not CE or ME	59	2.64	1.10	1.32	6.40	7.45 (31)	n/a	n/a

Notes: CATS = Concept Assessment Tool for Statics. In computation of average grade, the following weights are used: A = 4, B = 3, C = 2, D = 1, F = 0, W (withdrawl) = 0. n/a= not applicable

Although not part of the target population of this study, Table 2 includes a separate description of the students in Mechanical Engineering because of the stark difference in performance between this cohort and all other students. We have since learned that this is not an aberration in our data; rather, over the last decade, students entering Mechanical Engineering have a significantly stronger academic profile than students entering other majors in our College of Engineering.

Table 2 also reveals that of the 49 students in the target Civil Engineering cohort, only 15 completed the course with a C or better AND with a passing grade in Calculus II, which is also a prerequisite for Mechanics of Materials I. Of these 15 students, only 7 continued into the targeted section of Mechanics of Materials for Spring 2013. A primary reason for the large number of qualified students declining to continue was due to conflicts with other courses.

It is difficult to assign absolute meaning to the course grade. One problem is that the average assessed grade varies widely from instructor to instructor. The average assessed grade by the authors teaching the targeted sections is somewhat below their own historical averages over the last few semesters, but this could be dominated by the fact that the incoming grade point average and average grade in Calculus I of the Fall 2012 students was also lower than for our own students in recent semesters.

The scores on the Concept Assessment Tool for Statics (CATS) [cihub.org] are similar to recent trends at our campus. Grades in Statics and scores on the CATS correlate somewhat positively with the students' prior background, i.e., their overall GPA and their grade in Calculus I (the determination of a strict quantification of this relationship is still in progress). At the end of the Fall 2012 semester, 12 students from Civil Engineering who were not in the targeted sections also took the CATS. Both the average score and GPA of these students (10.27, 2.96) was higher than the average score and GPA of the students in the targeted sections (8.47, 2.68), which again raises the question of whether the CATS score is dominated by grade point average, i.e., suggesting that overcoming misconceptions held by weaker students (as measured by GPA) is difficult.

Furthermore it is unclear that the CATS is the best indicator of progress in our course because the CATS questions are conceptual and not procedural. While we would like to believe that procedural use of simulation tools to investigate behavior of statics problems leads to conceptual understanding of static principles – and in fact we attempt to ask questions in the modules that emphasize concepts – we have not yet verified this with the CATS or any other evidence. Furthermore, some of the concepts that we test in our modules are different than the concepts in the CATS.

It is also difficult to assign absolute meaning to the scores on the projects. The average grades on the projects are less varied by discipline, possibly due to the fact that the projects were completed in groups of 3-4 in which disciplines were mixed. However, a number of important trends were observed, including:

- many students (at least 50%) resisted using the spreadsheet and used in minimally; we were surprised by the number of students who chose to do a number of "side calculations" manually and then enter these numbers into the spreadsheet, rather than performing them directly in the spreadsheet; students who did this were at a general disadvantage to answer some of the more conceptual questions that required a variation in parameters to illustrate trends in behavior.
- a significant number of students were uncritical in accepting the values of their answers; for example, in Module 2, several students reported displacements that were more than 2 orders of magnitude too great; a generalization of this uncritical attitude is the belief that "computers are always right";
- an interesting misconception was discovered in Module 3: many students believed that the stresses would be higher at the top of the post than at the bottom because the peak wind force intensity occurred at the top of the post.

We also distributed a detailed 25 question survey at the end of the semester to inquire about students' impressions of the course. At total of 71/146 students completed the survey, including 24/49 in the target Civil Engineering cohort. We provide a summary of the key responses of this cohort as they are of most interest to our project.

Question 1 (open-ended) on the survey asked "In general, what concepts or skills do you think your instructors wanted you to learn with the projects?". After reading and coding the responses, we discovered that 10 students identified basic statics concepts, 5 identified advanced concepts from mechanics of materials, 12 identified some aspect of critical thinking or direct reference to simulation, and 10 identified something related to professional practice, realistic problem-solving, or group work [note that the total number of responses here, 37, exceeds the number of respondents, 24, because some students' answers corresponded to multiple codes].

Questions 2-6 were closed-form questions that asked students to react to certain statements. Table 3 provides a summary of these questions and responses.

Table 3. Responses to questions related to the modules, referred to here as "projects".

Statement → Response:	2. "The projects introduced me to realistic aspects of real engineering projects and design problems".	3. "The projects required me to think creatively and/or to discover things that were not explicitly given".	4. "The projects helped me to learn basic concepts of statics".	5. "The projects gave me a good preview of the next course in Mechanics of Materials".	6. "I did not like the projects because they added new concepts to the course that are not normally part of Statics; I would rather wait until Mechanics of Materials to learn these concepts".
Strongly agree	18	12	18	15	0
Somewhat agree	4	10	4	6	2
Neutral	2	2	2	3	7
Somewhat disagree	0	0	0	0	9
Strongly disagree	0	0	0	0	6
Overall average	3.67	3.42	3.67	3.50	1.21

Notes: the overall average is the average of all responses weighted by number of respondents for each response and using the values Strongly agree = 4, Somewhat agree = 3, Neutral = 2, Somewhat disagree = 1, and Strongly disagree = 0.

Overall, in considering the responses to Questions 1-6, it appears that the students have at least some understanding of our objectives, and respond favorably.

We also probed student opinions about the use of the spreadsheet. When asked "List what you think are both the advantages and disadvantages of using the spreadsheet in this or a similar course", many responses (25) indicated that the spreadsheet is efficient and/or prevents errors; a lesser number of responses (6) seemed to recognize the larger value of being able to able to vary parameters to understand system behavior.

We asked several additional questions about the use of the spreadsheet in a closed format. The student responses here are overall favorable, although this somewhat contradicts their reluctance to use the spreadsheet in the projects. Several students indicated that they were not familiar with the spreadsheet and that there was a learning curve required to get accustomed to using it. Table 4 summarizes the results of student attitudes with respect to the spreadsheet.

Table 4. Responses to questions related to the use of the Excel spreadsheet.

Statement → / Response:	11. "Because I did not have to do calculations by hand, the spreadsheets allowed me to focus my attention on understanding the concepts and the meaning of the results".	12. "When I used the spreadsheets I felt uncomfortable because I felt that I should have been doing the calculations by hand instead".	14. "The spreadsheets allowed me to solve my problems in an organized manner and allowed me to correct errors more easily".	15. "In future classes, I intend to use spreadsheets more often, even if the professor does not mention it, because they will help me to be more efficient".	16. "As a result of this class, I have increased my understanding of why computer tools are essential to the engineering design process".
Strongly agree	12	0	17	11	18
Somewhat agree	4	6	4	7	3
Neutral	5	8	3	5	3
Somewhat disagree	1	4	0	1	0
Strongly disagree	2	6	0	0	0
Overall average	2.96	1.58	3.58	3.17	3.63

Notes: the overall average is the average of all responses weighted by number of respondents for each response and using the values Strongly agree = 4, Somewhat agree = 3, Neutral = 2, Somewhat disagree = 1, and Strongly disagree = 0.

Finally, another set of questions asked students what they thought about the level of effort required for this class, and whether the effort was worth it. Nearly all students in the Civil Engineering cohort (23/24) reported that the class required above average effort, and most students (15/24) reported that the effort was worth it (similar results were reported by the non-CE students).

Discussion and Conclusions

In implementing this project we believe that our project is headed in the right direction, but that some important modifications are necessary. We perhaps overestimated the students' ability to use the spreadsheets without explicit instruction; we will address this in the next semester by being both more explicit with our instruction and expectations. We also believe that it is necessary to be more explicit in explaining some techniques that we expect, such as the skill to use the spreadsheet to vary parameters to understand system behavior and make design choices. We feel from our experience that some students really did cross a threshold of mature use where they did use the spreadsheet to critique answers and make informed design decisions. But a number of students had problems ranging from the mechanics of the spreadsheet to being uncritical or over-accepting of the results.

The quantitative performance data thus far collected does not demonstrate any learning gains as a result of our methodology. In particular, it is not clear whether the CATS is the right tool to measure learning gains as a result of our modules. Furthermore, it appears that the CATS scores need to be adjusted to account for GPA and math grades. Moreover, it is simply too early in the project to know the subsequent performance of the targeted students in the sequel courses Mechanics of Materials I, Mechanics of Materials II, and Structural Analysis. We are hopeful that in the longer range we will, in fact, see a difference in student performance among the cohort of students who took Statics and Mechanics of Materials with the modules developed by our project.

Finally, next semester (Spring 2013) will be the first introduction of new modules in the Mechanics of Materials I course. Some of these modules will strategically build off of the modules introduced in statics, whereas others will be new. We plan, in particular, to introduce at least one module that incorporates the use of finite element analysis software. While we believe that spreadsheets serve an important introduction to the idea of simulation in Statics, it is important to expose students to other engineering software that can handle more elaborate types of problems.

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