Work in Progress: Assessing development and retention of engineering design skills over the course of an undergraduate program in civil engineering

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Abstract

Understanding and using the engineering design process is a core aspect of any undergraduate engineering program. Typically, incorporation of the engineering design process begins early in the engineering program and is showcased in a culminating experience or capstone. This Work in Progress paper includes preliminary insights into curricular practices for two courses in a civil engineering degree. The first course is a one-semester, second-year seminar lab that was recently structured to integrate engineering design into activities that were traditionally non-design in nature. The engineering design process is woven throughout the course in three labs featuring different civil engineering disciplines and a semester-long design project. Through scaffolding and repetition, students work through problem definition, criteria development and forming an evaluation matrix multiple times over the course of the semester. The second course is a capstone design course that is taken in the final semester. Students complete a project based on a real-world problem and are guided by the instructor and external mentors.

We assessed students' abilities to apply the engineering design process in both classes. In the second-year seminar lab, we examine students' success over time with writing problem descriptions and needs statements, generating design criteria, and recognizing design constraints. Through repeated practice, students' abilities increased, which was partly measured by the number of attempts required to achieve specifications set by the instructor. Student self-reported confidence with engineering design before and after the lab course indicates that confidence increased for the majority of students. Similarly, we assessed students' abilities to apply the engineering design process in the capstone design course, and we compared results across two groups: those who had taken the second-year seminar lab and those who had not. A higher proportion of capstone teams with members completing the sophomore class earned passing scores compared to teams where no members completed the sophomore class. The results are expected to inform department practice on the effectiveness of repeated practice in developing and retaining engineering design skills.

Keywords: engineering design, capstone design, first-year engineering, spaced repetition, specifications grading

1. Introduction

The engineering design process is considered to be a core aspect of any engineering program. Indeed, to meet ABET accreditation requirements, all engineering programs must address student outcomes, which includes the application of engineering design. Adoption of the ABET EC 2000 Criteria in 1996 prompted an increase in engineering design emphasis in the curriculum, such as through capstone design courses [1]. A majority of capstone courses surveyed were initiated after 1990 [2], with first-year engineering design courses becoming popular shortly after this time [3]. While capstone design courses are intended to demonstrate knowledge and skills in engineering design for graduating students, first- and second-year engineering design courses play a role in student retention and identity. These introductory design courses are associated with greater student retention [4–7], as well as increased self-efficacy [8–10] and engineering identity [11].

Another goal of a first-year engineering design course is to prepare students for upper-level design courses and the capstone course. However, mastery of engineering design requires repeated practice. One learning approach for long-term retention is spaced repetition, where concepts are frequently encountered over time through instruction and review. Spaced repetition is known to be more effective than mass review (i.e., cramming) over a short period [12]. While this approach has not been applied extensively in engineering, it has been used in language learning [13–14], law [15], math [16–19], natural science [20] and medicine [21].

This paper focuses on an intervention in an early engineering design course (second-year seminar lab) and students' success over time with the engineering design process. The intervention emulates spaced repetition by having students use engineering design in multiple activities during the semester course. Repetition is also present though specifications grading, where students are required to achieve certain specifications (pass/fail) in order for an assignment to be considered complete [22]. Students may undertake as many attempts as needed to meet the specifications, which leads to repeated practice. Through the second-year seminar intervention, it was hypothesized that students undergoing repeated practice with the engineering design process would be more successful in their senior year capstone design course than students who had not completed the second-year seminar.

2. Background information about the curriculum and institution

2.1 Overview of civil engineering curriculum at the University of Nevada, Las Vegas

The civil engineering curriculum at the University of Nevada, Las Vegas (UNLV) is fairly typical. Year one involves prerequisite courses in English, math, chemistry, geology and physics, along with general education courses. Most students take the first-year engineering seminar (one semester) and introduction to surveying. Students begin to take core civil engineering courses in their second year, as well as a second-year, one-semester engineering seminar. Year three consists of required engineering courses, and students complete the remaining required and elective engineering courses in their final year. The capstone course is taken in the final semester of study.

Design-based or design-intensive courses are embedded throughout the curriculum. Students are introduced to engineering design in the first-year engineering seminar; however, this course is not specific to civil engineering and does not include a design project. The first required project is featured in the second-year engineering seminar as part of a 1.75 hr/wk lab for civil engineering and construction management students. In the latter half of the degree, students take one required design-intensive course (concrete structure design) and two elective design courses. Then they complete the capstone design course in their final semester. As a result, there are a minimum of five design-based/design-intensive courses spread across three years of the curriculum.

2.2 Second-year engineering experience at UNLV

This course is designed to provide sophomore students with an interactive engineering experience through a team-based project using the engineering design process and activities that target the various civil and environmental engineering and construction disciplines: construction management, environmental, geotechnical, structural, transportation and water. A major goal is to introduce students to the breadth of civil and environmental engineering and construction management topics, and to acquaint students with new technology and innovations used in these fields. Activities incorporate engineering ethics, design thinking, project management, teamwork, and communication. In addition, the course supports overall student learning through the use of metacognitive learning strategies, familiarization with university and college resources, and development of software skills.

Certain phases of the engineering design process were featured heavily in the course activities. These included developing a project description and need statement, identifying design criteria and constraints, generating design alternatives, evaluating design alternatives, and justifying the recommended solution. Scaffolding of the engineering design process is incorporated by working through the phases of the design process and adding one phase as a time. Also, students are asked to revisit steps and make changes since the design process is iterative.

One unique aspect of the course is specifications grading, which uses a pass/fail system for assignments and minimum completion rates associated with letter grades. Each assignment has a rubric that indicates the ‘specs’ for completion. If ‘specs’ are not met, the assignment must be revised and resubmitted. Examples of the rubric and grading specifications are provided as Tables 1 and 2, respectively.

Table 1. Example specifications rubric for an assignment on a problem description and need statement.

Format – Submitted as Word document or PDF with headings	Correct Submitted as a single Word document or PDF with headings (problem description, needs statement, reflection)		Incorrect Not submitted as a Word document or PDF, or submitted as multiple documents, or missing headings for components
Completion – Includes a problem description, needs statement and reflection paragraph	Correct All three components are included		Incorrect One or more component is not included
Content – Problem description accurately describes the scenario	Excellent Includes details (5Ws + H) and is concisely written as a cohesive paragraph	Adequate Includes most of the important details in a paragraph and may or may not be concisely written	Insufficient Very little detail is included (more than two of the 5Ws + H are missing) or information is provided as a list
Content – Needs statement is clear, concise and accurate	Excellent Statement is accurate yet doesn't narrow potential solutions. Length is no more than two sentences.	Adequate Statement makes sense but might be a little vague or too narrow. Length is no more than two sentences.	Insufficient Statement doesn't make sense for the scenario or is more than two sentences.
Content – Reflection paragraph	Excellent Paragraph is 100-400 words, has specific details on what you learned about defining a problem, and shows clear evidence of reflecting on what was learned/practiced	Adequate Paragraph is 100-400 words, is somewhat general about what you learned for defining a problem, and includes a reflection on what was learned/practiced	Insufficient Paragraph is less than 100 or more than 400 words, doesn't state what was learned for defining a problem or doesn't present any reflection on what was learned/practiced

Note: If your submission is marked for any of the gray-shaded regions, then the submission will receive an "R" score, and resubmission will be required to earn credit for completion.

Table 2. Example of specifications grading system for the second-year engineering seminar course.

Earned grade	# of Missed Assignments	# of Missed Quizzes	# of Absences / Non-participation Days	# of Missed Project Assignments	# of Exploration Activities
A	1	0	2	0	3
A-	1	0	2	0	2
B+	2	1	3	0	1
B	2	1	3	0	0
B-	2	1	4	0	0
C+ …	3	2	4	1	0

2.3 Capstone design course at UNLV

The final semester capstone course, taken in the last semester of undergraduate study, engages students in the civil engineering design and construction process from project planning through project objectives, collection of relevant site information, development and analyses of alternative solutions in light of constraints, design calculations, and recommendation of a final alternative. Team efforts in oral, written, and graphical communications are also evaluated. The written communication is a 20-chapter project report covering the above-described topics.

3. Assessment methods and analysis

3.1 Second-year engineering experience: Embedded engineering design assessments

Three individual assignments were assessed for students in sections A (n=17) and B (n=12) receiving the same instruction and completing the same assignments in the Fall 2024 semester. Data for three prior cohorts (Fall 2021, 2022, 2023) are available and could be examined in the future; however, only one cohort was included for this work-in-progress paper. Assignment 1 focused on writing a problem description and need statement. Assignment 2 focused on writing criteria and constraints and distinguishing between them. Assignment 3 focused on developing alternative solutions. The engineering design process was included in a team project via three reports, but this analysis does not include those reports since group grades were awarded. The data collected from Assignments 1-3 are the number of attempts to pass the assignment (i.e., meeting the specifications). Analysis includes the first-time pass rate for each assignment, and a comparison of the total attempts per student per assignment. Some students enrolled in the course are not civil engineering or construction management majors; their scores are excluded from the analysis because lack of motivation may have played a role in assignment completion.

3.2 Second-year engineering experience: survey on confidence with engineering design process

The second assessment for the second-year engineering seminar was self-reported confidence with the engineering design process. As part of a survey in the final week of class, students were asked two consecutive questions

1. My confidence with the engineering design process before the start of this semester was…
2. My confidence with the engineering design process after this semester is…

with response options: Terrible, Poor, Average, Good, Excellent. Data were collected for three cohorts (2021, 2022, 2024). The cohort from 2023 was missed due to extenuating circumstances that interrupted the entire institution at the end of the semester. The response counts and response rates were as follows: 2021 = 31 responses with 91% response rate; 2022 = 27 responses with 90% response rate; 2024 = 35 responses with 90% response rate. For data analysis, the response options were coded as 1, 2, 3, 4, 5 for Terrible, Poor, Average, Good, Excellent.

Some students enrolled in the course are not civil engineering or construction management majors; however, their scores could not be excluded since the survey is completed anonymously. Considering that the vast majority of students are at least engineering majors, they completed the course activities, and the survey only took a few minutes to complete, responses from non-civil engineering or construction management students are still considered to be reliable.

3.3 Capstone design course: Project Report assessments

Each chapter of the capstone report is evaluated during the semester against a rubric, shared in advance with students, that provides specific evaluation criteria at levels from A (90-100%) to F (less than 70%) for each capstone report chapter. Sets of completed chapters are submitted at different levels of design completion throughout the semester, similar to what is experienced in engineering practice (e.g., 30% design submittal). We selected four capstone chapters that aligned with the engineering design steps in the sophomore course exercises, which were:

Chapter 1: Rationale and Project Objectives
Chapter 12: Identification of Design Constraints
Chapter 13: Development of Design Alternatives
Chapter 18: Analysis of Alternatives and Selection of Final Alternative

The rubric's rating criteria from 90-100% to less than 70% for each chapter are shown in Table 3. Score ratings decrease when teams submit chapters with insufficient detail, errors or irrelevant information. Team submissions are evaluated per the rubric on first submission. Teams may subsequently revise report chapters per the rubric evaluations and resubmit. First submission chapter scores are evaluated in this paper.

Table 3: Rubric with rating criteria for team-submitted capstone course chapters

	Grade A or A- 90-100% of max points	**Grade B+, B, B- 80-89% of max points**	**Grade C+ or C 70-79% of max points**	**F, Fail 0% - 69% of max points**
Chapter 1: Rationale and Project Objectives. Need and problem to be solved	Initial project objectives clearly address all stated client needs. All-important major and minor objectives are identified and appropriately prioritized. With an accompanying narrative.	Initial Project objectives clearly address all stated client needs. All major objectives are identified but one or two minor ones are missing, or priorities are not established with accompanying descriptive narrative.	Initial Project objectives address some stated client needs.	Initial Project objectives are absent or do not address client needs.
Chapter 12: Development of and discussion about relevant project design constraints	All relevant constraints are identified and accurately analyzed in a complete error-free narrative**.**	Most constraints are identified; some are not adequately addressed or accurately analyzed in a complete 1-3 grammatical error narrative.	Few or no constraints are identified, or some constraints are identified but are not accurately analyzed. Or narrative is complete with > 3 grammatical errors.	Discussion of constraints is irrelevant to the project or missing (0 points) from the report or are arbitrary with no reference to relevant project site attribute data.
Chapter 13: Generation of three design alternatives integrated across both technical areas that satisfactorily address constraints	Three or more alternatives are generated and thoroughly described including materials of construction. Preliminary dimensionally accurate rendering of each one is provided.	Three alternatives are generated and adequately described including materials of construction. Preliminary renderings provided but are not dimensionally correct.	Only one or two alternatives are considered. Renderings are absent or are rough hand-drawn sketches.	Alternatives not discussed or are inappropriate to the site; copied from other projects. Renderings are absent.

	Grade A or A- 90-100% of max points	Grade B+, B, B- 80-89% of max points	Grade C+ or C 70-79% of max points	F, Fail 0% - 69% of max points
Chapter 18: Narrative describing analysis of alternatives and justifying selection of final alternative	Each alternative is appropriately and correctly analyzed for technical feasibility using a decision matrix with thorough supporting calculations and dimensions including numerical estimates of expected performance. Best design alternative recommendation is well supported by (*integrated with)* the information. Justification for selection of preferred alternative is clearly presented with reference to all supporting data and decision matrix.	Appropriate alternative analyses are employed for each alternative, but report uses decision matrix with very brief supporting calculations and dimensions that don't permit a numerical estimate of expected performance. Best design alternative recommendation is mostly supported by the information. Justification for selection of preferred alternative is presented with reference to most of supporting data and decision matrix.	Appropriate alternative analyses are employed in a decision matrix without supporting calculations. Recommendation for best design alternative is not supported by information collected. Justification for selection of preferred alternative is present but incomplete, either using matrix without data or data without matrix.	Alternatives not discussed and/or analysis or rationale for alternative is limited or absent. Best design alternative recommendation is arbitrary without data. Justification for selection of preferred alternative is absent or arbitrary without reference to supporting data or decision matrix.

4. Results and discussion

4.1 Repeated instruction for the engineering design process

Three individual assignments that incorporate the engineering design process were assessed based on the number of attempts to meet the assignment specifications. The first-time pass rates on Assignments 1-3 for Section A (n=17) were 88.2%, 64.7% and 35.5%. The first-time pass rates on Assignments 1-3 for Section B (n=12) were 58.3%, 41.7% and 66.7%. It was expected that first-time pass rates would improve as students gained experience with the engineering design process and reading specification rubrics. However, this did not occur. In addition, the number of attempts on each assignment was compared across time for each student to identify any trends, which were categorized as consistently passing, inconsistent, improving over time or declining over time. In Section A, 29% of students consistently passed the assignment on the first attempt, 0% showed improvement over time (i.e., fewer attempts to meet specifications), 18% were inconsistent and 53% showed a decline (i.e., taking more attempts to meet specifications). Similarly, Section B results were 25% consistently passing, 25% showing improvement, 33% inconsistent performance and 17% showing a decline. More specific assessments could be used to determine if students are performing better in applying the engineering design process. For example, many students missed a specification related to formatting in Assignment 3, which has no bearing on the design process. To really identify improvement in applying the engineering design process with repeated instruction, new assessment methods will be needed.

Students' self-reported confidence with the engineering design process was assessed through a survey. Data from three cohorts (2021, 2022, 2024) all indicate that the majority of students were more confident with the engineering design process after the course. A summary table for each cohort is presented as Table 4. The average change was an increase in confidence by 1.1, 0.8 and 0.8 for cohorts 2021, 2022, and 2024, respectively. This trend is also seen by the majority of students indicating an "Average" confidence before the course and "Good" confidence after the course. In all cohorts only one student indicated below average confidence by the end of the semester. Considering that this may have been students' first time actively applying the engineering design process, it is reasonable that the majority rated their confidence as "Good" rather than "Excellent." Responses where students indicated a decrease in confidence could mean that students lacked extensive experience in applying the design process and thought they were knowledgeable until actually working through the steps. However, qualitative information is lacking to make any judgments on why confidence decreased. In future assessments, an open-ended question (e.g., "What contributed to the change in your confidence?) could shed light on what caused students to become more confident. In addition, students could be asked their confidence with the engineering design process at the beginning of class, and these results could be compared to the "pre" responses as a check for response accuracy.

Table 4. Student responses for the second-year engineering seminar on self-reported confidence with the engineering design process.

	2021		2022		2024	
Counts	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Terrible	2	0	1	0	0	0
Poor	9	1	3	1	9	1
Average	15	6	13	4	19	8
Good	5	20	10	17	6	22
Excellent	0	4	0	5	1	4
	2021		2022		2024	
	Count	%	Count	%	Count	%
No change	7	23%	7	26%	7	20%
Increase	24	77%	19	70%	26	74%
Decrease	0	0%	1	4%	2	6%
	2021		2022		2024	
Average change	1.1		0.8		0.8	
Minimum change	0		-1		-1	
Maximum change	4		2		2	

4.2 Comparison of students' abilities to use the engineering design process

Sophomore engineering lab class rosters starting in Fall 2021 were compared to capstone class rosters to identify capstone teams with student members who had completed and had not completed the sophomore class. Reviewing all capstone teams (n = 18) registered for the Spring and Fall 2024 semesters, nine teams were identified that had one or more previous sophomore class participants. The remaining nine teams over the Spring and Fall 2024 semesters did not contain members had previously completed the sophomore class.

Scores of the four submitted chapters of the nine sophomore-completion member teams were compared to the nine teams where no team members completed the sophomore class, using an ‘acceptable’ score threshold of 70% or greater. Results are shown in Table 5.

Table 5: Comparison of frequency of acceptable (70% or greater) scores for first team submission. Higher frequency is shown in **bold face**.

report chapter # and title	**Without sophomore lab. Percent of teams completing chapter with scores > 70% (n=9 each chapter)**	**With sophomore lab. Percent of teams completing chapter with scores > 70% (n = 9 each chapter)**
1 - Rationale & Objectives	89%	**100%**
12 - Design Constraints	78%	**100%**
13 - Design Alternatives	78%	**89%**
18 - Analysis of Alternatives	89%	89%
All four chapters	83%	**94%**

Table 5 shows that for three of the four evaluated chapters (Chapters 1, 12, and 13), higher proportions of capstone teams with members completing the sophomore class earned scores > 70% compared to teams where no members completed the sophomore class. Consolidated results shown in the last row of Table 5 (n = 36) also indicate that there was a higher overall proportion (94%) of teams earning scores > 70% for all four chapters on teams where at least one student completed the sophomore lab compared to teams where no members had completed the sophomore lab (83%). A two-tailed paired Student’s t-test of the above data with the null hypothesis (H_0) that the sophomore lab would have no effect on capstone performance, generated a computed p-value of 0.03, rejecting the H_0 at a confidence level of $p < 0.05$, and accepting H_1, the alternative hypothesis that the sophomore lab likely had a positive effect on capstone team performance.

5. Conclusions and future work

Preliminary findings from the study indicate that repeated instruction benefitted civil engineering and construction management students for both short- and long-term outcomes. While short-term performance did not consistently improve across assignments using the available assessments, students self-reported an increase in confidence with the engineering design process. With regard to a long-term outcome, students who completed the second-year engineering seminar performed better than peers on selected capstone engineering design tasks compared to those who did not complete the second-year engineering seminar.

Certain aspects of the study could be improved in a future iteration. For example, assessments used to evaluate student growth in applying the engineering design process in the second-year seminar could be revised to be more specific to growth in engineering design and eliminate unassociated aspects of specifications grading (e.g., not passing an assignment due to a formatting error). Student self-reported confidence can be objectively compared to performance following the method used in [23]. Qualitative questions could be added to the survey in order to understand what contributed to the self-reported change in confidence. Alternatives to team-based project reports are needed for both courses in order to assess individual student outcomes. For example, individually completed student capstone homework exercise scores could be classified on the basis of sophomore class completion or non-completion and evaluated to see if sophomore class participants as a group perform better than those who did not complete the class.

We aim to continue to assess the second-year engineering seminar intervention in subsequent semesters as additional students who previously completed the sophomore design lab undertake the capstone course.

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