INCREASING STUDENT CONFIDENCE THROUGH EXPERIENTIAL DESIGN EXERCISES IN ENGINEERING SCIENCE COURSES

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ABSTRACT

This study investigates the impact on student confidence of completing in-lecture engineering design activities focused on the application of specific engineering science topics within a materials engineering course. Many times, engineering science courses are taught with the expectation that the course content can be easily translated by students at a later time to apply in engineering design activities. By measuring student self-reported confidence across several related topics before and after completion of the in-lecture design exercises the impact of the exercises on student confidence has been quantified. On average, students have a lower than desired confidence in applying the specific materials engineering topics to a design problem after completing only the course content on the subject. Following completion of the related seventy-five minute design exercise, student confidence increased by a statistically significant degree. These results suggest that close integration of topical content learning with design application activity may be a useful method to improve engineering student confidence and, by extension, retention.

Keywords: Student confidence, Design education, Education, Design learning

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1 INTRODUCTION

Student design experience varies across institutions of higher learning. Introductory engineering conceptual design courses have become common in the United States and are frequently used to communicate a design process or problem approach and to define terminology with the intent of the process and terms guiding student design work for the remainder of their undergraduate experience (Besterfield-Sacre, 1998; Dym, 2005). Most programs re-engage the design process through the use of a stand-alone integrative capstone experience, challenging students to apply their engineering science and systems training to design problems provided by instructors or industry and community partners. While some programs seek to reinforce the design process training in the intermittent years, many do not comingle the design process with instruction in other science and engineering topics, seemingly establishing a divide between learning the engineering sciences and the application of engineering science toward design problems, potentially impacting student confidence and retention (Brennan, 2013). Indeed, even the terms used for design problem definition may become unclear in the context of an engineering science homework problem set. Confidence in application of engineering science to design problems is enhanced not only by mastery of the science content but also its relevant and appropriate application. The impact of reduced student confidence level may disproportionately impact students by race and gender (Cech, E, 2011; Chachra, D, 2009; Colbeck, C.L., 2001; Litzler, 2014; Moakler Jr, 2014). Different pedagogical approaches have been demonstrated to impact student confidence (Ellis, 2003; Hutchison-Green, 2008) and retention (Geisinger and Raman, 2013) particularly in engineering design (McKenna, 2005) but also in other fields such as mathematics (Parsons, 2009).

This study follows students in an introduction materials engineering course who are provided engineering design challenges related to topics of interest within the materials engineering context. These problems follow the style of Dym (2013) in terminology used to define a design problem in terms of functions, objectives, and constraints. The design space is severely limited to a set number of materials with the relevant data provided in tables. Students are asked to select the best material to meet the design goals. The broad set of topics covered on these exercises include elastic and plastic deformation, tensile failure, creep and relaxation, impact, and fatigue. Problems are narrowly defined in the earlier part of each exercise and become increasingly challenging later in each design exercise. through reduction in constraints for more advanced problems. Within each topical design problem set student designers are challenged to address conflicting objectives without clear user priorities and must justify their decisions. The former type of problem is closer to a straightforward homework or exam problem requiring the best answer for a well-defined question while the latter type of design problem is closer to those experienced by designers in industry who are asked to meet conflicting objectives without the benefit of unambiguous paradigms mathematically balancing the conflicting objectives. For many students this is the introduction to the responsibility of the designer to address undefined or prioritized objectives by creating an equation expressing their interpretation of the objectives and explicitly stating where their interpretation would reverse. In this way, the design applications of engineering science are in line with the professional practice expectations of the engineering field by advancing Kolb's (1974) stages of learning from abstract conceptualization to active experimentation. While students do not always appreciate the impact of example or case-based activities on their learning (Yadav, 2019), an argument can be made that confidence is an important aspect of perceived self-efficacy.

As an example, students may be asked to select the best material for a tie rod so that it best meets objectives of being lightweight (total mass) and having low environmental impact (with embodied energy serving as the surrogate metric for environmental impact). Through analysis, they discover that the lightest tie rod material does not result in the lowest embodied energy. This begins a series of conversations about the value of lower mass compared to embodied energy, the responsibility of the designer not to robotically select the "best" material but to consider the impact of that decision for the user, society, and the environment, and also the ability to determine the resulting quantification of their decision. Though students are not told which objective to prioritize or to what extent, some students realize their decision can be quantified.

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Stated conversely, the choice between materials can be quantified to better inform student design decisions and establish conditional selections. As an example, we may presume the lightest tie rod material is 100 [g] lighter than the lowest environmental impact tie rod material, which is 100 [kJ] lower in embodied energy. Selection of the lightweight rod implies that the value of 1 [g] of mass reduction is valued as at least 1 [kJ] of embodied energy reduction. With this knowledge, students will report selecting the lowest mass rod to satisfy the "be lightweight" objective, but only if the value of a gram reduction in mass exceeds or equals the value of a kilojoule reduction in embodied energy. If not, the choice should switch to the less environmentally impactful rod.
Some students will argue that the second lowest mass rod with the lowest embodied energy is "light enough" and that they are reducing environmental impact through their decision to prioritize reduction of embodied energy. This statement is typically shared without effort to quantify the decision. This has sparked interesting discussions about the energy used to move the tie rod's additional mass during its in-service lifetime and the related increase in environmental impact. This energy can also be estimated (with some assumptions about the service conditions of the tie rod).

2 STUDY

This study considers the impact of four design exercises related to material selection in an introduction to materials engineering course on student design confidence (Alias, 2009). The course was taught for two semesters at a small liberal arts college focused on science, engineering, and mathematics undergraduate education. The design exercises (DEs) cover the topics of DE1: yield, ultimate tensile strength, strain; DE2: creep and relaxation; DE3: impact; and DE4: fatigue and were completed in numerical order. The four exercises are each conducted in two parts over approximately half of two seventy-five-minute lectures. That is, about thirty-seven and a half minutes of lecture time is nominally assigned for each half of a design exercise. This time was controlled by having students complete the assignment entirely or almost entirely during lecture. As such, the time required to complete this intervention may be balanced against any benefits derived and compared to other potential interventions. Students were required to demonstrate the calculations they applied in their design process and to explain the reasoning of their material selection but were permitted to consult with others in the course on the best approach to the problems and how to address ill-defined problems.

Students were asked to complete online pre-assessment and post-assessment surveys for each of the design exercises describing the degree of confidence they had in their ability to design across several measures related to the exercise topic. All students have completed all readings, lectures, and homework on the topic of each design exercise prior to attempting the exercise in class. The pre-assessments were submitted prior to attending the lecture with the first part of each design exercise but after all instruction on the topic applied through the exercise. The post-assessments were submitted following completion of the design exercise. As a result, differences in the pre-exercise and post-exercise self-reported student confidence are attributable to participation in the exercise and not to additional instruction on the topic of the design exercise or to scores received for their work. The specific survey statements changed with each DE topic other than statement 3, considering generation of a design performance metric, which was consistent across all design exercises. The data from each design exercise are presented independently and include data from different terms of instruction. For all questions, a single 9-point Likert scale was used to establish the student's confidence in response to questions related to the design exercise activity, Table 1. A 9-point scale was chosen to permit finer responses in confidence levels without requiring selection of extremes. Each question is tested statistically using a paired Student's T-test with a null hypothesis that the design exercise intervention does not improve the student's degree of confidence with respect to each statement pre and post exercise.

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Table 1. Nine-point Likert scale of student responses to their degree of confidence in response to the statements offered in pre activity and post activity design exercise surveys for the four design exercises conducted. This same scale is used for every response in this study.

1	no confidence
2	highly unconfident
3	moderately unconfident
4	mildly unconfident
5	neither confident or unconfident
6	mildly confident
7	moderately confident
8	highly confident
9	absolute confidence

3 RESULTS AND STATISITCAL TREATMENT

3.1 Design Exercise 1

The first design exercise considered a tie-rod under tension. Students were asked to select from a list of 8 materials (properties provided: Youngs Modulus, Yield Strength, Ultimate Tensile Strength, Density, Cost (per kg.), and Embodied Energy). The functions, objectives, and constraints were varied over four cases focusing on total mass, cost, embodied energy and mass, and cost with a free variable in the range of acceptable rod radii. The changes in the objectives and constraints were deceptively simple but resulted in significant challenges for student designers. The number of participating student subjects varied by term for this study; fall 2021 n = 7, spring 2022 n = 11, combined n = 18. Throughout this document, the results of the survey are presented for the pre activity and post activity. Average values of data are reported in Figure 1. Confidence intervals of 95% are shown. Students are asked to respond to the five following survey statements.

Survey Statement 1: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for material selection decisions.
Survey Statement 2: I am confident in my ability to select the best material for a tie rod design to minimize cost, weight, embodied energy, or other factors of interest.
Survey Statement 3: I am confident in my ability to generate a design performance metric separated by Function, Geometry, and Material.
Survey Statement 4: I am confident in my ability to select the best material for a tie rod design so that it will not yield or such that it will not break.
Survey Statement 5: I am confident in my ability to select the best geometry and material combination for a tie rod design so that it will not yield or such that it will not break and be lowest cost, mass, or other factors of interest.

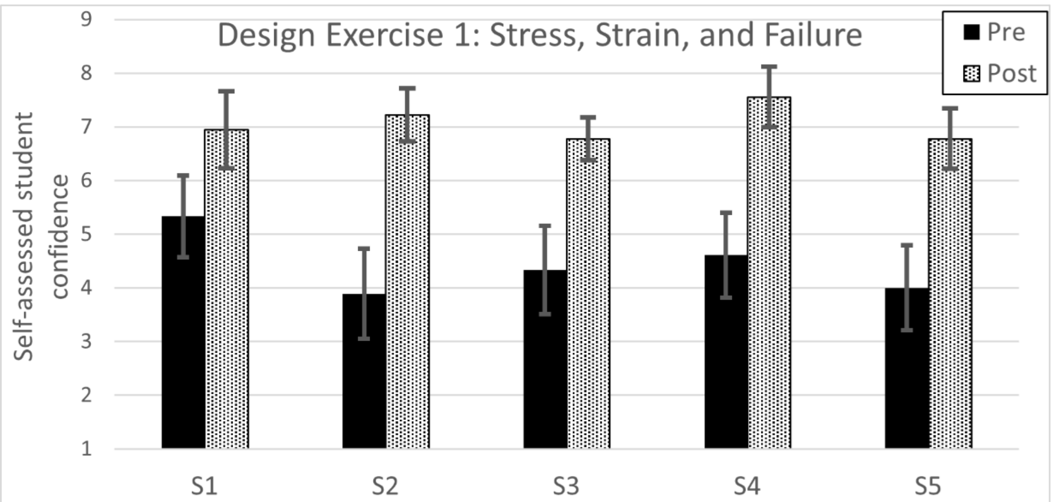

Figure 1. Student responses indicating confidence across the five statements surveyed for Design Exercise 1. Confidence bands indicate 95% confidence intervals.

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3.2 Design Exercise 2

Design exercise 2 considered a disc subject to a constant displacement compression under an elevated temperature (relaxation) and a tie-rod under a constant loading under elevated temperature. Students were to find the lightest or lowest cost material from 8 provided for each condition. Variations in test temperature or duration were included as part of the problem conditions. The number of participating student subjects varied by term for this study; fall 2021 n = 22, spring 2022 n = 10, combined n = 32. Results are shown in Figure 2.

Survey Statement 1: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for creep.
Survey Statement 2: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for relaxation.
Survey Statement 3: I am confident in my ability to generate a design performance metric separated by Function, Geometry, and Material.
Survey Statement 4: I am confident in my ability to select the best material for a spring design so that it will not creep unacceptably.
Survey Statement 5: I am confident in my ability to select the best material for a spring design so that it will not undergo unacceptable relaxation.

Figure 2. Student responses indicating confidence across the five statements surveyed for Design Exercise 2. Confidence bands indicate 95% confidence intervals.

3.3 Design Exercise 3

In design exercise 3, students considered a simplified model of a car bumper subjected to impact loading at different temperature conditions. They had to select the best material for a provided list of 8 choices that best met requirements for being low cost, lightweight, and environmentally low cost. In addition, geometry variations were permitted in some cases. The number of participating student subjects varied by term for this study; fall 2021 n = 13, spring 2022 n = 15, combined n = 28. Results are shown in Figure 3.

Survey Statement 1: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for a design that must absorb an impact load.
Survey Statement 2: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for a design subject to impact load at cold temperatures.
Survey Statement 3: I am confident in my ability to generate a design performance metric separated by Function, Geometry, and Material.
Survey Statement 4: I am confident in my ability to select the best material for a spring design so that it will absorb the required energy with consideration of potential ductile to brittle transition.
Survey Statement 5: I am confident in my ability to select the best material and geometry combination for a bumper design so that it will meet the objective of being environmentally sustainable.

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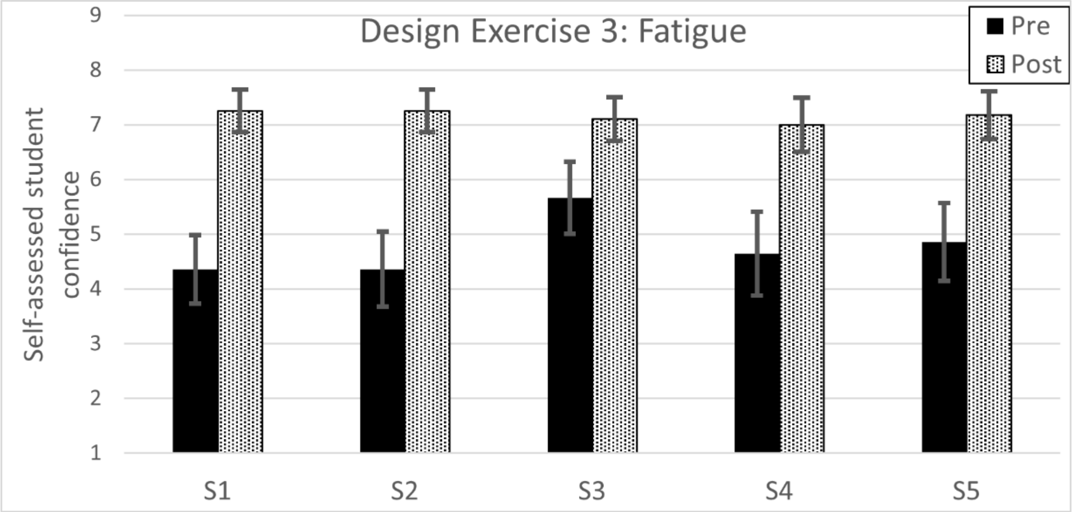

Figure 3. Student responses indicating confidence across the five statements surveyed for Design Exercise 3 in fall of 2021 and spring of 2022. Confidence bands indicate 95% confidence intervals.

3.4 Design Exercise 4

Design exercise 4 focused on the topic of fatigue. Again, eight materials with their properties and fatigue testing data were available to the students. This considered a design problem of a cyclically loaded tie rod in tension. Goals included making a lightweight tie rod that had a proscribed lifetime, a low-cost tie rod with a higher lifetime, a low cost and low embodied energy tie rod with a proscribed lifetime, and a tie rod of longest possible lifetime and low embodied energy. The number of participating student subjects varied by term for this study; fall 2021 n = 14, spring 2022 n = 15, combined n = 29. Results are shown in Figure 4.

Survey Statement 1: I am confident in my ability to translate design objectives, functions, and constraints into the parameters required for a design that must work under cyclic loading.
Survey Statement 2: I am confident in my ability to alter geometry as a design parameter to accommodate cyclic loading.
Survey Statement 3: I am confident in my ability to generate a design performance metric separated by Function, Geometry, and Material.
Survey Statement 4: I am confident in my ability to select the best material for a tie rod design subjected to cyclic loading of a defined minimum number of cycles.
Survey Statement 5: I am confident in my ability to select the best material and geometry combination for a tie rod design subjected to cyclic loading to optimize for different objectives.

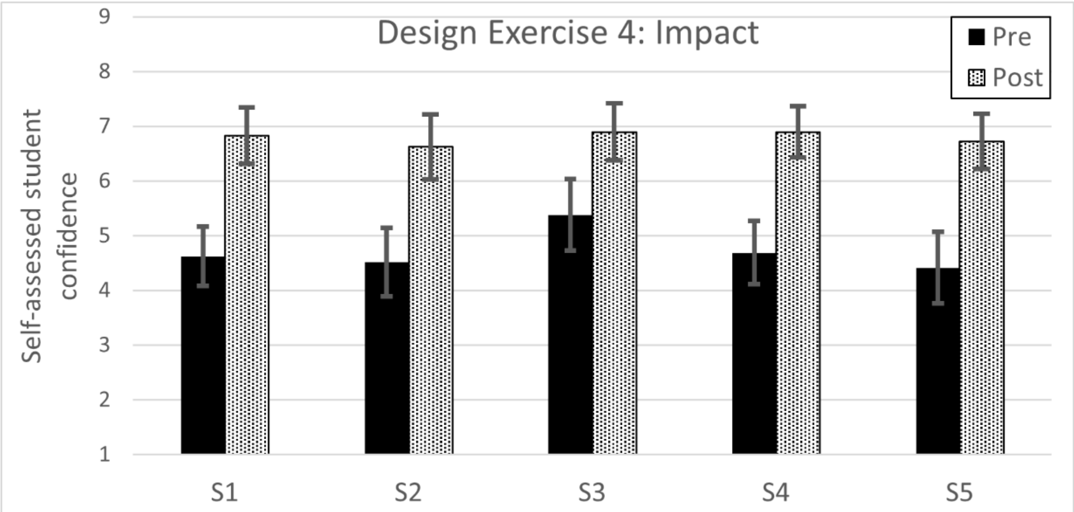

Figure 4. Student responses indicating confidence across the five statements surveyed for Design Exercise 4. Confidence bands indicate 95% confidence intervals.

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3.5 Statement 3 across design exercises

It is interesting to note that one statement was repeated for each design exercise. This statement, statement 3, was relevant to all the design exercises in that it generally described confidence in translating a set of statements to a performance metric. The number of participants for each term is the same as previously described in the individual design exercises. Results are shown in Figure 5.
Survey Statement 3: I am confident in my ability to generate a design performance metric separated by Function, Geometry, and Material.

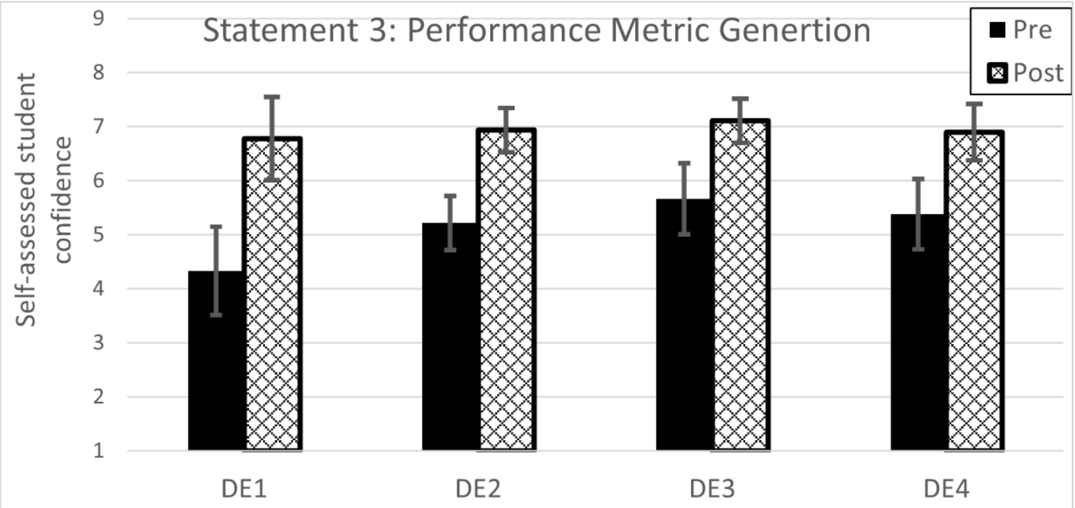

Figure 5. Student responses indicating confidence for statement 3 surveyed across the four Design Exercises. Confidence bands indicate 95% confidence intervals.

3.6 Statistical treatment and results

The statistical significance of differences in the student responses to the statements for the four design exercises were evaluated using two-tailed, paired Student T-tests. To correct for Type II errors, the Holm-Bonferroni Correction is applied to maintain an alpha of 0.05 or 95% confidence. The corrected alpha value for each statement of each design exercise is listed in Table 2 as HBC. Results shown in Table 2 indicate that the differences between initially self- reported student confidence and post design activity self-reported student confidence for each test.

Table 2. Statistical significance of the pre-activity and post-activity responses for statements 1 through 5 across the Design Exercises determined with two-tailed, paired Student-T tests. The alpha value is corrected for Type II errors using the Holm-Bonferroni method to maintain a 95% confidence level. Values in bold are statistically significant at greater than the 95% confidence level.

	DE1		DE2		DE3		DE4	
	P-Value	HBC	P-Value	HBC	P-Value	HBC	P-Value	HBC
Statement 1	**3.4E-04**	0.050	**3.4E-10**	0.010	**4.1E-11**	0.010	**6.9E-08**	0.013
Statement 2	**4.8E-08**	0.010	**2.3E-09**	0.013	**2.9E-10**	0.013	**3.1E-06**	0.025
Statement 3	**3.0E-05**	0.025	**5.8E-09**	0.017	**1.5E-04**	0.050	**2.4E-04**	0.050
Statement 4	**1.7E-07**	0.013	**5.0E-07**	0.050	**1.0E-06**	0.025	**5.6E-08**	0.010
Statement 5	**1.4E-06**	0.017	**2.2E-08**	0.025	**2.6E-07**	0.017	**2.2E-07**	0.017

The significance of statistical differences in the student initial responses (pre-activity) to the initial response to statement three across for the four design exercises were evaluated using two-tailed Student T-tests (non-paired). To correct for Type II errors, the Holm-Bonferroni correction is applied to maintain an alpha of 0.05 or 95% confidence. The corrected alpha value for each statement of each design exercise is listed in Table 3 as HBC. Results in Table 3 indicate that the only statistical difference is between the initial confidence for the first exercise compared to the initial confidence in the second design exercise.

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Table 3. Statistical significance between the pre-activity responses for statement 3 across the Design Exercises determined with two-tailed (non-paired) Student-T tests. The alpha value is corrected for Type II errors using the Holm-Bonferroni method to maintain a 95% confidence level. The value in bold is statistically significant at greater than the 95% confidence level.

	P-Value	HBC
Design Exercise 1 to 2	**0.048**	0.050
Design Exercise 2 to 3	0.528	0.025
Design Exercise 3 to 4	0.549	0.017

4 DISCUSSION

The initial average confidence level of students for these design topics directly related to the course work on the topic covered including homework problems, hands-on laboratory exercises, and quizzes on the design exercise specific material was below the "neither confident nor unconfident" rating. It is reasonable that educators would hope for a higher confidence in applying engineering science topics directly to their associated design applications. In each statement examined for the design exercises, students improved their self-evaluated confidence by a statistically significant degree, typically from about 4.6 (between mildly unconfident and neither confident nor unconfident) to about 7.0 (moderately confident) following completion of the seventy-five minute exercise. The initial confidence in student ability to apply the topical course content would not have considered the issues of competing interests in design explicitly, but students would have been aware of the trade-offs required following completion of the exercises.

Statement three remained constant throughout the design exercises. It may be expected that the confidence on this specific topic would remain at an increased level for subsequent design exercises. This was only the case for increased confidence observed between the first exercise and the second and subsequent design exercise. It may be that a degree of confidence is retained related to statement 3 which is generally applicable to all design activities but a lack of confidence with respect to the specific application of the new topical knowledge persists.

Together, the statistically significantly increasing confidence following the topical design exercises and a moderate persistent increase in statement three confidence suggest that while the design exercises are effective in increasing confidence, that degree of confidence is partially specific to the topic covered in the specific design activity. Stated differently, the transferability of activity confidence is somewhat limited by the specific material applied in the exercises. This would indicate that design exercises should be developed that cover the material of interest specifically with respect to transfer of confidence on the same design activity but applied to a different topic from that previously explored appears limited.

In this study, a seventy-five-minute lecture was dedicated in total to each design exercise. It is not clear that student confidence has plateaued even on a specific topic basis following this educational intervention. It may be that shorter design exercises could positively influence student confidence to some extent or that the design exercises might be better applied as extended homework problems. Qualitative observation by the author suggests that, following a period of struggle, students approached each other or the instructor for clarification or assistance in framing the design problems. It appeared that these exchanges guided the approach students adopted to generating solutions but not the priorities they set for solving the incompletely defined aspects of the exercise. For example, if asked to identify a design that is lightweight and low-environmental impact, a student might seek peer assistance in understanding how to calculate the mass or environmental impact of a design or how to identify the factors that might be adjusted within the constraints. Nevertheless, the student was unlikely to accept their peer's relative order of importance of these objectives, and therefore was likely to choose a different specific design solution from their peer.

5 UTILITY FOR EDUCATORS

It is frequently assumed that application of engineering science course material to design activities is simply a natural and obvious extension of the learning outcomes of a course. This study suggests that even in the case of direct application of freshly completed content, students lack confidence in the application of the topical knowledge to design. Programs my find it challenging for students to develop confidence applying engineering sciences to design without topically relevant exercises.

Instructors have many methods to examine and measure a student's understanding of and ability to apply course content. It may be beneficial with respect to design application for instructors to select exercises on the application of topical knowledge with respect to developing student confidence. Of the many activities that instructors may choose to enhance student design confidence, the investment of approximately four seventy-five-minute lectures across a twenty-seven-lecture term may appear onerous. However, this class exercise time might be effectively offset with out of class video lectures or reductions in homework or other assignments. It remains to be seen if the application of knowledge to design exercises also enhances the fundamental understanding of the foundational material. Alternatively, the five hours of design exercise and consultation might be tried outside of class with some degree of consultation permitted on problem approach during lectures. Regardless of the approach or total time investment, student application of course material in design increases student confidence in ways that working with the course material alone does not.

6 CONCLUSION AND FURURE WORK

A benefit of design exercises for increasing student confidence applying topical material from an introduction to materials engineering course is observed. This benefit suggests that increased attention focused on application of engineering science course knowledge might benefit student design confidence more broadly if applied in engineering courses. Important open questions remain.

Investigation of the impact of exercise duration is of interest to the author and may be of use to the engineering design education community. It would be beneficial to have a clearer understanding of the trade-off between design confidence, confidence persistence, and student time investment on design exercises. It may be that briefer, focused exercises might be sufficient to result in similar increases in student confidence. Alternatively, it may be that longer exercises might be necessary for greater persistence or degree of student design confidence.

Quantifying the difference across sex, race, or ethnicity in student confidence applying course content in design would be helpful for instructors. The response to the design exercises in this study were not found to differ by sex, race, or ethnicity significantly primarily due to low power with respect to the number of participants when evaluated across these categories. Despite an approximately even split between male and female students, the number of respondents coupled with small class sizes made this analysis challenging. Additional investigations will hopefully increase study power to address this open question.

The influence of setting of the design exercises in not well understood. This study conducted the design exercises in a controlled classroom during lecture. While this permitted an immediate response to student issues or confusion, it also prevented a more generalized understanding of the influence of setting or assignment type (homework vs. in-class, for example). It would be good to know the degree to which success depends on an in-class setting for the design exercises to increase student confidence.

Finally, objective performance in application of knowledge may not necessarily be linked to student confidence. It would be helpful to understand the degree to which both design applying the course content improves and the degree to which student mastery of the course content improves through its application in design exercises.

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