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Implementing an Engineering Math Curriculum Sequence: Preliminary Results and Lessons Learned

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Implementing an Engineering Math Curriculum Sequence: Preliminary Results and Lessons Learned

This **Complete Evidence-Based Practice** paper details an engineering math curriculum sequence for first-year engineering students belonging to the General Engineering Learning Community (GELC) at Clemson University. The paper begins with a discussion of the rationale for an engineering math curriculum followed by an explanation of Clemson's approach, a report of preliminary results, and recommendations for interested practitioners and instructors. Additional details about the GELC program are available in previous papers [8], [9].

The first-year engineering math curriculum at Clemson was implemented to explain to students why basic math knowledge is relevant to engineering. While the expectations of engineering students within university programs and professional industry require them to learn course concepts, connect their learning to real-world contexts, and build a knowledge base easily transferable across disciplines [1], [2], the reality often involves a more segmented, siloed approach by students. Artificial barriers imposed between disciplines, along with a disconnect in course material and authentic experiences outside of academic curricula, can make the use of applicable knowledge difficult for engineering students, especially at the outset of their schooling. Most notably, many first-year engineering students lacking prior higher level mathematical exposure struggle with the integration of engineering and mathematics concepts, viewing their mathematical training as abstract and disjointed when removed from real-world applications [3], [4]. With many of these introductory mathematics courses acting as gatekeepers for advancing within an engineering program, the result of disconnected math and engineering concepts can lead to decreased student motivation, lower academic performance, and reduced retention within engineering courses and majors at the university level. Additionally, the divide between mathematics and engineering departments' foundations and expectations for students can also cause frustration among faculty. As a solution, an integrated engineering math curriculum, often taught by the engineering faculty at a given institution, has been proposed and even implemented at several colleges and universities [4], [5], [6].

As a leader in this curriculum shift, Wright State University developed an engineering math curriculum for incoming first-year engineering students over fifteen years ago [4]. The National Model for Engineering Mathematics Education is a Wright State initiative supported financially through the National Science Foundation (NSF). Once identified as at-risk of not passing calculus, engineering students first enroll in an engineering math course followed by the "normal" calculus sequence in subsequent semesters. This sequencing provides students with additional time and space to build their academic and mathematical maturity in preparation for the higher cognitive load necessary for successfully completing calculus. The engineering math course focuses on providing students with a solid understanding of foundational mathematics concepts and their applicability within the engineering field. Drawing on longitudinal student performance in Science, Technology, Engineering, and Mathematics (STEM) courses, students' self-reported perceptions of the engineering math course, and overall retention data, this approach has been shown to increase students' academic success in future STEM courses [7].

Building off the Wright State model, the engineering department at the Ohio State University designed a comparable engineering math curriculum sequence [6]. Their course is offered to incoming engineering students lacking prerequisite calculus experience to ease the bottleneck blocking students from beginning engineering coursework. In addition to mathematics content, the course also incorporated college success strategies into the curriculum.

Taken together, the results of an engineering math course at the first-year university level suggest students are more motivated to learn and apply math concepts, are just as prepared for future course work as students who begin by enrolling in calculus, and are more likely to continue into and graduate from an engineering major than students not enrolled in this program [6], [7]. While the goals of the engineering math curriculum at Clemson are similar to those of Wright State and Ohio State, including increased student retention, motivation, and overall engagement and success in engineering content, our approach is unique in a number of ways.

Clemson's approach to engineering math curriculum

At Clemson, the GELC program was created in 2017 to increase retention for engineering students entering the university with low calculus readiness skills. Identified as "not calculus ready" by university math placement exam scores, eligible students are approached during summer orientation sessions and voluntarily enroll in the program upon their entry into the university in the fall semester. However, the approach taken by Clemson is more extensive than past implementations at other colleges and universities, with a holistic experience including multiple novel components. Two primary components include cohorting students in sections of their STEM courses during the first year and co-enrollment in a learning strategies and professional skills course during the first semester [9], [10]. The ultimate goals of the GELC program are to increase student retention in engineering majors and strengthen students' skills as future engineering professionals. In an effort to bolster the chances of achieving these goals, the engineering math course outlined below was introduced in Fall 2019.

Course content and materials

Ratton & Klingbeil's *Introductory Mathematics for Engineering Application* [11] and Stephan et al.'s *Thinking Like an Engineer* [12] are the primary texts used to guide the course. The overarching course outcomes listed within the syllabus include preparing students for the rigor of future engineering and mathematics classes, providing students with a solid foundation of basic engineering skills, and introducing students to the different engineering majors and career options. As seen in these outcomes, the course attempts to draw overt connections between math concepts and engineering by keeping the focus on developing a deeper understanding of engineering as a field.

Throughout the course, student learning objectives pertain to mathematical concepts, though their presentation to the students emphasizes the role of engineering. This emphasis is intentional and plays a large role in the decision to have engineering faculty exclusively teach this curriculum to students in the GELC program. By the end of the course, students should be able to:

- identify elements within a mathematical model (i.e., slope, area under the curve, shape of a line) and their relation to physical attributes represented through a graph
- determine graphical solutions to problems
- determine the values of and relationships among specific components of a mathematical model
- apply mathematical models to authentic, real-world problems
- interpret and draw conclusions from graphical, tabular, and other numerical representations of data
- summarize and justify analysis of mathematical models for problems
- express solutions to problems using an appropriate combination of words, symbols, tables, or graphs.

Figure 1 contains an outline of the specific topics covered and the number of 50-minute class sessions dedicated to each. The graphic reflects topics covered during the Fall 2020 iteration of the course to provide the most recent picture of the course content.

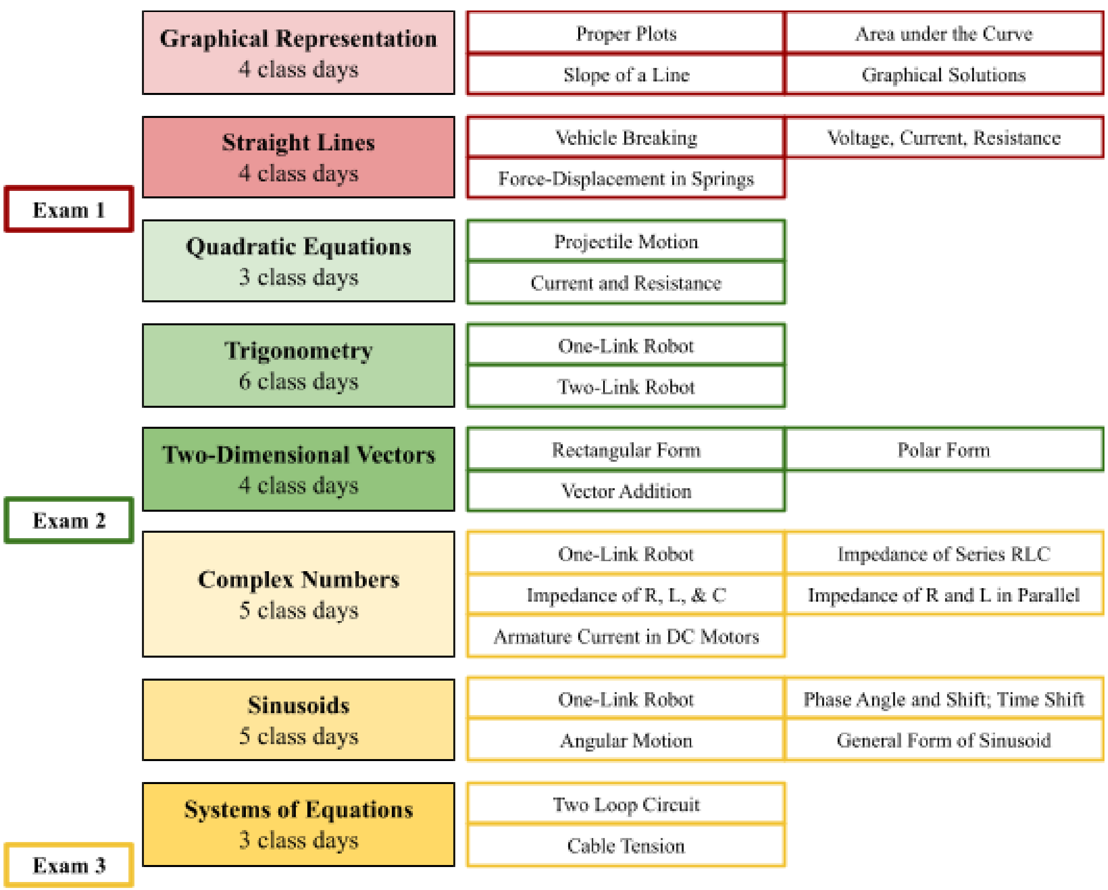

Figure 1. Engineering Math Course Topical Outline

An additional course component complementing the in-class content and objectives is the Assessment and Learning in Knowledge Spaces (ALEKS) [13] modules. To place into subsequent math courses, students are required to take a math placement exam. The ALEKS modules allow students to learn about, practice, and self-test across a wide range of math concepts covered on the placement exam.

Course structure and logistics

The 3 credit hour course met in-person during Fall 2019 and in a hybrid method (i.e., some in-person and some online) during Fall 2020 due to Clemson's COVID-19 protocol. In Fall 2019, there were two sections taught by one instructor. In Fall 2020, there were three sections taught by one instructor. Table 1 outlines the percentage of students' grades allocated to each course component.

Table 1. Engineering Math Course Grade Allocation

Course Component	**% of Final Grade**
ALEKS Practice Work	10%
University-Based Math Placement Exam Result	20%
Homework	10%
Exams → 3 at 15% each	45%
Final Exam	15%

The overall goal of this paper is to determine if the engineering math curriculum at Clemson appears to enhance subsequent success for students. In the current investigation, "success" primarily entails retention in an engineering major and grades in math and engineering courses following the engineering math course. Our preliminary investigation seeks to answer the following questions:

> *Research Question 1:* How does engineering math performance relate to students continuing at the university and into an engineering major?
>
> *Research Question 2:* What is the progression of students in math courses following enrollment in the engineering math course?
>
> *Research Question 3:* What is the relationship between engineering math final grade and final grades in subsequent STEM courses? In other words, is success in the engineering math course a predictor of success in future math courses? Similarly, is success in the engineering math course a predictor of success in future engineering courses?

Methods

The focus of this paper is success following the engineering math course; therefore, only students from the Fall 2019 cohort (n=76) are included in the analyses, as complete data were not yet available for students in the Fall 2020 cohort. Students who dropped the course prior to the end of the semester (n=4) were excluded from the analyses, leaving a sample size of 72. All students enrolled in the engineering math course were first-time first-semester undergraduates in general engineering. Table 2 includes additional demographic characteristics of all students enrolled in the course and students in the general engineering program overall.

Table 2. Fall 2019 Engineering Student Demographic Characteristics

	General Engineering Overall		**Engineering Math Students**	
	N	**Percent**	**N**	**Percent**
Total Enrollment	974	100%	76	100%
Female / Male	262 / 712	26.9% / 73.1%	22 / 54	28.9% / 71.1%
Non-White / White	210 / 764	21.5% / 78.4%	31 / 45	40.8% / 59.2%
Out-of-State / In-State	358 / 616	36.8% / 63.2%	12 / 64	15.8% / 84.2%
First-Generation	127	13%	25	32.9%

At the time of this writing, course enrollment and final grade data were available from Fall 2019, Spring 2020, Summer 2020, and Fall 2020; all were obtained from a university database and used in the analyses. To answer the first and second research questions, descriptive statistics were run. Comparative analyses, specifically one-way analyses of variance (ANOVA), were conducted to answer the third research question.

Results

The division of students by final grade in the engineering math course, along with students' demographic characteristics, is presented in Table 3. Demographic characteristics are included to provide a broad context of student breakdown by grade compared to total course enrollment and the university's total General Engineering population presented in Table 2.

Table 3. Student Demographic Characteristics by Engineering Math Grade

	Female [n (%)]	**Male [n (%)]**		**Non-White [n (%)]**	**White [n (%)]**
A (n=9)	2 (22.22%)	7 (77.78%)		3 (33.33%)	6 (66.67%)
B (n=27)	9 (33.33%)	18 (66.67%)		8 (29.63%)	19 (70.37%)
C (n=22)	7 (31.82%)	15 (68.18%)		11 (50%)	11 (50%)
D (n=6)	1 (16.67%)	5 (83.33%)		3 (50%)	3 (50%)

F (n=8)	1 (12.5%)	7 (87.5%)		3 (37.5%)	5 (62.5%)
Total (n=72)	*20 (27.78%)*	*52 (72.22%)*		*28 (38.89%)*	*44 (61.11%)*

Research Question 1: How does engineering math performance relate to students continuing at the university and into an engineering major?

Information related to students' continuation in an engineering major, a non-engineering STEM major, or a non-engineering non-STEM major is presented in Figure 2. Information is also included regarding the number of students who unenrolled from the university. As expected, students who earned higher grades in the engineering math course were more likely to continue into an engineering major than those receiving lower grades. Moreover, of students continuing in engineering through Fall 2020, those with higher grades in the engineering math course were more likely to be accepted into the major for their specific engineering discipline than those receiving lower grades.

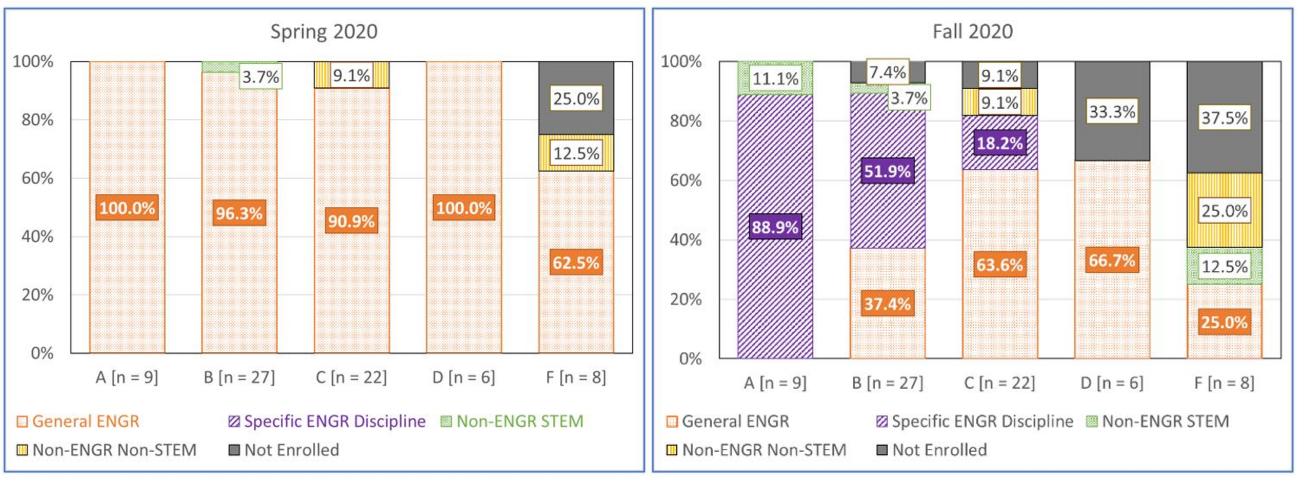

Figure 2. Spring 2020 and Fall 2020 Majors

Research Question 2: What is the progression of students in math courses following enrollment in the engineering math course?

The engineering math students' progression through math courses at Clemson can be seen in Table 4. The majority of students place into and are able to continue through the suggested math sequence following enrollment in the engineering math course. A final grade of a C or higher is needed for students to advance to the next math course. As part of the elongated calculus sequence, students taking engineering math in their first fall semester are recommended to take the second calculus course in the summer following their first year to stay on track with students who initially placed into the first calculus course. Students in the GELC program are eligible for an award funded by the Boyd Foundation to cover the cost of registration, housing, and meals during the summer term to ease the financial burden of enrollment over the summer.

Table 4. Subsequent Enrollment in Math Courses

	Fall 2019	Spring 2020	Summer 2020	Fall 2020
Mathematical Concepts as Applied to Engineering	72 (100%)*			
Precalculus		5 (6.94%)		
Precalculus and Introductory Differential Calculus		17 (23.61%)		
Differential and Integral Calculus or Calculus of One Variable I		41 (56.94)*	18 (25%)	6 (8.33%)
Calculus of One Variable II		1 (1.39%)	36 (50%)*	19 (26.39%)
Calculus of Several Variables		1 (1.39%)		33 (45.83%)*
Not Enrolled in Math Course Relevant to Engineering		7 (9.72%)	18 (25%)	14 (19.44%)

*target course for given semester

Research Question 3: What is the relationship between engineering math final grade and final grades in subsequent STEM courses? In other words, is success in the engineering math course a predictor of success in future math courses? Similarly, is success in the engineering math course a predictor of success in future engineering courses?

To answer this research question, data were collected from students' enrollment in subsequent math and engineering courses for Spring 2020, Summer 2020, and Fall 2020. Regardless of the courses they placed into, student letter grades were transformed into numbers (A=5, B=4, C=3, D=2, F=1, not enrolled=0). For pass/no pass classes, including "Precalculus" and "Precalculus and Introductory Differential Calculus," students' pass scores were coded as 4 and students' no pass scores were coded as 1. An average grade for the three semesters was calculated for each student. If a student was not enrolled during the summer session, the average contained only scores for the Spring 2020 and Fall 2020 semesters. Figure 3 demonstrates a positive relationship between a student's grade in the engineering math course and success in future math and engineering courses.

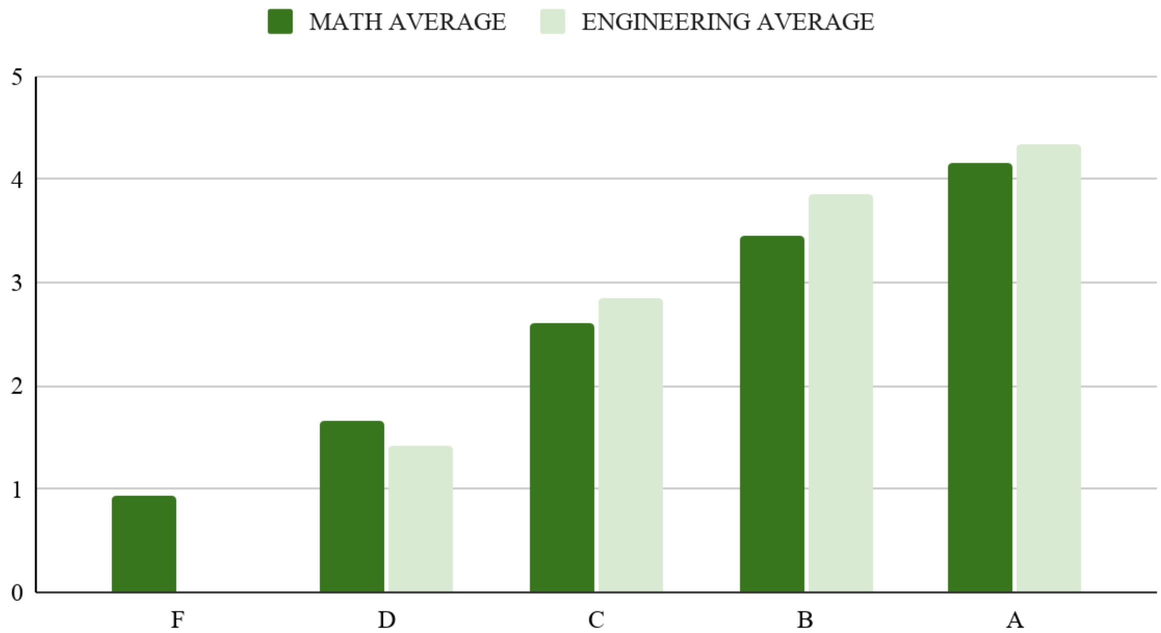

Figure 3. Average Subsequent STEM Course Grades by Engineering Math Course Final Grade

We conducted a one-way analysis of variance (ANOVA) to determine if there were significant differences in future success in mathematics courses based on students' final grades in the engineering math course. The ANOVA yielded significant results ($F(4,67) = 13.769$, $p < 0.001$). This suggests there is an overall meaningful difference in future math grades between students in different engineering math grade groups (i.e., A, B, C, D, F).

We then conducted multiple comparisons to reveal where significant differences exist between students in each grade group. The results are summarized in Table 5, with the mean difference in subsequent math grades listed in the table and their significance level indicated through asterisks. Students with an A in engineering math earned significantly higher grades in subsequent math courses than students with a C ($p = 0.005$), D ($p < 0.001$), or F ($p < 0.001$) as their final grade in engineering math. Students with a B in engineering math earned significantly higher grades in subsequent math courses than students with a D ($p = 0.004$) or F ($p < 0.001$) as their final grade in engineering math. Students with a C in engineering math earned significantly higher grades in subsequent math courses than students with an F ($p = 0.003$) as their final grade in engineering math.

Table 5. Post-Hoc Comparison of Mean Differences for Subsequent Math Grades

	A	B	C	D	F
A		0.72	1.56***	2.5****	3.23****
B			0.84	1.78***	2.52****

C				0.94	1.67***
D					0.73
F					

$p \leq 0.001$: **** | $p \leq 0.01$: *** | $p \leq 0.05$: ** | $p \leq 0.10$: *

Similarly, the ANOVA conducted to determine if there were significant differences in future success in engineering courses between students based on their final grades in the engineering math course yielded significant results ($F(4,67) = 16.329$, $p < 0.001$). The subsequent engineering courses included in this analysis were "Engineering Computer Skills" and "Engineering MATLAB Programming" taken by students still enrolled as general engineering majors in Spring 2020 and Summer 2020, respectively. These two courses are required in Clemson's General Engineering sequence, and students must complete them before moving into their specific engineering discipline. Therefore, this analysis does not provide insight into how engineering math course grade predicts success in one's discipline-specific engineering courses. However, the results of the ANOVA suggest there is an overall meaningful difference in general engineering course grades between students in different engineering math grade groups (i.e., A, B, C, D, F).

Multiple comparisons were again conducted to reveal where significant differences exist between students in each grade group. The results are summarized in Table 6, with the mean difference in subsequent engineering grades listed in the table and their significance level indicated through asterisks. Students with an A in engineering math earned significantly higher grades in subsequent engineering courses than students with a D ($p = 0.001$) or F ($p < 0.001$) as their final grade in engineering math. Students with a B in engineering math earned significantly higher grades in subsequent engineering courses than students with a D ($p = 0.002$) or F ($p < 0.001$) as their final grade in engineering math, while students with a C only earned significantly higher grades in subsequent engineering courses than students with an F ($p < 0.001$) as their final grade in engineering math.

Table 6. Post-Hoc Comparison of Mean Differences for Subsequent Engineering Grades

	A	B	C	D	F
A		0.48	1.49	2.92****	4.33****
B			1.01	2.44***	3.85****
C				1.42	2.84****
D					1.42
F					

$p \leq 0.001$: **** | $p \leq 0.01$: *** | $p \leq 0.05$: ** | $p \leq 0.10$: *

Discussion

The preliminary results suggest the engineering math course is well-suited to promote success in future STEM courses, specifically math and engineering. Results pertaining to the first research question demonstrate students with a higher final grade in the engineering math course are more likely to continue in engineering, at least into their second year. While these students may naturally be more motivated to persist in achieving their academic and professional goals, the results may also suggest students who engage in the engineering math course are learning to connect math and other STEM concepts to their future role as engineering professionals. The results of the second research question show the majority of students place into and are able to continue through the recommended math sequence following enrollment in the engineering math course. This demonstrates the structure and content of the engineering math course provides students with a solid foundation to draw from in future math courses.

The analyses for the third research question indicate success in the engineering math course, defined through a higher final grade, is a significant predictor of success in both subsequent math and engineering courses. Accordingly, there is a positive relationship between engineering math course grade and future math and engineering course grades. The post-hoc analyses also revealed statistically significant differences in subsequent math and engineering grades by engineering math course grade, with virtually every letter grade grouping experiencing significant differences in outcomes from those that were non-adjacent. For example, students with a B in engineering math earned significantly higher final grades in their subsequent math and engineering courses than students with a D or F. Meanwhile, there was no statistically significant difference in future math and engineering course outcomes between those with a B and those with an A or C in the engineering math course. This finding suggests unique differences exist between students in each engineering math grade group, though the underlying mechanisms causing these differences are outside of the scope of the current study. One interesting difference between final grades in subsequent math and subsequent engineering courses related to students earning a passing grade in the engineering math course. While students with an A in the engineering math course earned significantly higher grades in future math courses than students with a C, those same students did not earn statistically significantly higher grades in future engineering courses. Though additional investigation and long-term data are needed to understand this phenomenon, the preliminary finding suggests passing the engineering math course, regardless of letter grade, may provide students with an opportunity to succeed as engineering students.

Within the engineering math course, females received passing final grades at a higher rate than male students, with 90% of female students earning an A, B, or C in contrast to 76.9% of male students earning an A, B, or C in the course. The rate of passing was less pronounced by race/ethnicity, with 78.6% of non-white students receiving a passing grade and 81.8% of white students receiving a passing grade. Additional research should consider the mechanisms at play allowing students traditionally underrepresented in STEM majors to achieve passing grades at comparable or higher rates than traditional engineering students.

While these initial findings are promising, additional tracking of the original Fall 2019 cohort and subsequent cohorts is necessary to determine long-term effects of the engineering math curriculum. Additionally, these results would be strengthened by looking at a comparison group. While historical data prior to 2019 is available, student characteristics, university policies and curriculum changes, and disruptions brought about by the onset of the COVID-19 pandemic during the Fall 2019 cohort's subsequent courses throughout 2020 and 2021 are factors unable to be controlled for, making a meaningful comparison difficult to conduct. As a result, this paper was limited to discussing within-program comparisons. Though students' perceptions of the engineering math curriculum were not collected during the Fall 2019 semester, future tracking efforts should include student self-reports of the course's value at various checkpoints from the end of their first semester through graduation.

Recommendations and lessons learned

Though not expressly tied to the analyses conducted above, we felt it important to address recommendations and lessons learned after designing and teaching two iterations of the engineering math course.

The first offering of this course in Fall 2019 anecdotally revealed challenges related to students' prior knowledge and content. For example, students struggled with concepts related to trigonometry, a subject typically included within high school precalculus curriculum. Additionally, the initial pacing of the course made it difficult for students to ingest the material, so modifications to slow the pace of the course and to accommodate student needs while still offering meaningful, rigorous lessons were made. These modifications included more class days spent on content found challenging by students, such as trigonometry, and the alterations were made in the second iteration of the course in Fall 2020.

Several of our recommendations fall in line with those offered by the Ohio State team [6]. One of these includes targeting students for the fall cohort during summer orientation sessions. Specifically, we recommend marketing the curriculum to both eligible students and their parents using previous students' stories and other relevant data. Like Ohio State, we also advocate for concurrently teaching success strategies for college students (e.g., time management, collaboration skills, study and test-taking strategies, mental and physical wellness, etc.). During the same semester students take the engineering math course, our program requires students to co-enroll in a learning strategies course focusing on similar skills with an emphasis on professional development and academic skills.

Conclusion

This **Complete Evidence-Based Practice** paper outlines the implementation of an engineering math course at Clemson University. It provides an overview of the rationale for the curriculum, content and structure of the course, preliminary results from one cohort, and lessons learned. While the initial implementation of the engineering math course proves promising, additional data points from future iterations are needed to fully evaluate the efficacy of the curriculum in supporting first-year engineering students.

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