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A Survey Exploration of Finite Element Method Education and Self-Efficacy in Undergraduate Mechanical Engineering

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Introduction

Engineering is sometimes described as "design under constraint" [1], requiring engineers to engage in systematic decision-making to develop solutions to diverse problems. To make effective design decisions, engineers draw on evidence from a range of mathematical, scientific, and humanistic tools, including formulae, test procedures, and simulation software. As technological development accelerates—particularly through advances in computing power and artificial intelligence—the number and sophistication of available tools continues to grow. To realize the benefits of this expanding toolkit, modern engineers must develop the competencies needed to use these tools appropriately to make informed decisions under constraint.

Computer-aided engineering (CAE) tools are a critical class of design tools in mechanical engineering because they enable robust modeling and simulation. Common CAE tools include computer-aided design (CAD), computer-aided manufacturing (CAM), computational fluid dynamics (CFD), and finite element analysis (FEA). Although commercially available for decades, the use of these tools in professional engineering practice continues to increase [2]. FEA and the Finite Element Method (FEM) that underpins it are particularly important for mechanical engineers. FEM can be applied to the design, analysis, and improvement of nearly any mechanical system and enables analytical solutions to problems that are otherwise impractical or impossible. This capability enhances design evaluation and failure analysis, making familiarity with FEM and exposure to FEA software an expected outcome of undergraduate mechanical engineering education [3].

To prepare students for the CAE tools they will encounter in industry, most engineering programs provide access to software packages that include CAD and FEA. Instruction in FEM/FEA has gradually entered undergraduate mechanical engineering curricula, typically through upper-level elective courses. Historically, these courses targeted students intending to specialize in FEM, emphasizing deep theoretical understanding. However, as CAE tools have become ubiquitous in engineering practice, this specialist-focused model is no longer sufficient. While not all students require advanced theoretical mastery, all mechanical engineering graduates should have foundational exposure to FEM/FEA. This shift has prompted programs to integrate FEM content into the core curriculum [4], [5], [6]. Despite this trend, limited formal research has examined the current state of undergraduate FEM learning or identified optimal points in the curriculum for introducing FEM content. Understanding students' existing familiarity and competence is therefore essential to identifying gaps between current preparation and expected outcomes at graduation.

This exploratory study addresses this gap through a survey of upper-level undergraduate mechanical engineering students at a large, public, four-year university in the United States. We examined students' exposure to multiple types of CAE tools through coursework and extracurricular experiences, with particular attention to their interest in learning FEM/FEA and their perceived self-efficacy with FEM theory and software. By documenting students' typical experiences, this study contributes to the growing body of research on FEM teaching and learning in mechanical engineering. The study was guided by the following research questions:

1. Where in their undergraduate experience do mechanical engineering students gain exposure to computer-aided engineering content?
2. How do undergraduate ME students rate their interest in learning FEM and their competency with FEM theory and software?
3. To what extent do undergrad ME students develop finite element self-efficacy?

Background

To contextualize our investigation of FEM education for undergraduate ME students, this section reviews relevant literature covering the use of FEM in industry, teaching and learning FEM, and self-efficacy theory. This extant body of research informed our conceptualization, execution, and analysis of this study.

Origins of Computer-Aided Engineering

FEA technology of today is built upon the foundations of continuum mathematics, engineering and computational advancement. The concept of representing a continuum via discretized elements traces back to Archimedes and has been utilized throughout history as one of the only ways to decompose complex continua. It was not until the scientific and technological boom of the post-World War II era that these principles were applied to structural and modeling problems. The first iterations of computer-aided engineering tools began to develop and differentiate due to parallel advances in theory and computing technology.

The Finite Element Method began in the 1940s with simple models that could be verified by comparison to plane elasticity theory, but was accelerated by the recognized utility of matrix methodology to scale the approach [8]. Matrix-based representation of elements in a geometric continuum were easily translatable to different element and load types. Furthermore, matrix format made data easy to upload to early computers, enabling large-scale calculations. Building upon the initial direct stiffness approach, FEM pioneers introduced energy-based principles such as minimum potential energy and virtual work to expand the breadth of structural problems that could be modeled. Energy approaches also opened the doors for new thermal and fluid branches of the FEM [2]. The field of Computational Fluid Dynamics (CFD), while based in similar matrix methods of discretization, incorporates finite volume methods rather than finite elements. Commercial software using FEM and CFD methods was not available until the 1970s when computing power was sufficient and widespread enough to support FEA.

Computer-aided design (CAD) developed on a similar timeline as FEA but with independent inspirations. Rudimentary graphics developed during World War II for radar technology spurred some of the first civilian work in computer modeling, and the beginnings of Computer Numerical Control (CNC) in manufacturing inspired interactive platforms for drafting and machining [9]. Like FEA, CAD technologies did not become commercially available until the 1970s and 1980s, but it would be several more decades before the individual engineer had access to CAD on a personal computer [10]. Today, CAE tools are seen as universal in engineering work. Technological advancements continue to add capability to CAE software on an ongoing basis, necessitating that engineers are familiar with these tools and adaptable to changing platforms.

Finite Element Analysis

The Finite Element Method is defined as "a numerical method for solving a system of governing equations over the domain of a continuous physical system" [11, p. 1] and can encompass structural, heat transfer, acoustics, and electromagnetic analyses. The most common use is for structural analysis based on continuum mechanics and the theory of elasticity.

The capabilities of FEM theory and FEA software today encompass an expansive range of linear and nonlinear mechanics, static and dynamic systems, multi-body systems, and abnormal geometries. Consequently, FEM has become a pillar of mechanical analysis for engineers in industry [2], [12]. A study of engineering job postings found that FEA skills were in the top 20 most mentioned skills for biomedical and civil engineering jobs [13]. In a survey study of experienced engineering professionals, Perez-Santiago and Campos studied the most important knowledge and skills for engineers interfacing with FEM [12]. They identified a variety of necessary skills, but a strong understanding of FEM procedure, analysis planning, part meshing, setting boundary conditions, and interfacing between CAD and FEA were the highest ranked. Collectively, these findings underscore the need for a holistic education in FEM to prepare engineers for contemporary industry practice.

FEM Education

Engineering educators have taken varied approaches to preparing students for the FEM techniques and FEA software used in industry. Early FEM instruction was largely confined to graduate programs due to limited computing resources, with upper-level undergraduate electives emerging as software became more accessible. This in-depth, elective model was well suited for students aiming to become FEM specialists. However, as FEM/FEA has become a routine tool across engineering practice, engineers are now expected to develop basic competencies with multiple CAE tools, prompting a shift in pedagogical approaches.

A review of recent research on FEM education in mechanical engineering shows that practitioners have developed modules, units, projects, and online courses to teach FEM throughout the curriculum [11]. FEM-related content is often embedded in statics, solid mechanics, and mechanical design courses [12], [13], while dedicated CAE or FEM courses remain common. These courses vary in emphasis, ranging from software proficiency [14] to broader considerations such as ethics [15] and human-centered design [16]. Overall, FEM instruction is increasingly integrated with core engineering content rather than isolated as a standalone topic.

Despite these efforts, significant challenges persist in integrating FEM into the ME curriculum. A central concern is the risk of producing incorrect or unreliable analyses, commonly described as "garbage in, garbage out," where simulation results depend heavily on the quality of user inputs. Students may overestimate the validity of FEA results when they lack sufficient theoretical understanding [17], [18], and misconceptions in solid mechanics can further impede proper model setup and interpretation [18]. Instructors also face practical barriers, including limited expertise, software access, and constraints on time and instructional resources.

Across published studies of FEM educational interventions, relatively little attention is given to the preliminary learning design processes that motivated these efforts. While many papers describe intervention content and outcomes, the basis for identifying instructional needs is often unclear. Needs assessment is a critical early step in curriculum design because it aligns instruction with students' backgrounds and learning contexts [19]. This study addresses this gap by characterizing undergraduate mechanical engineering students' experiences, interests, and competencies related to FEM.

Self-Efficacy of Technical Skills

The construct of self-efficacy is often defined as a person's belief in their capacity to execute behaviors necessary to achieve a certain performance [20]. Pioneered by psychologist Albert Bandura, self-efficacy is a construct grounded in social cognitive theory, which posits that learning occurs within the context of social experiences [21]. Many researchers have investigated self-efficacy in engineering education and found that it relates positively to degree persistence and success in engineering courses [22], [23]. To specifically measure students' self-efficacy with particular types of engineering content, researchers have developed psychometric survey scales for topics like design [24], programming [25], and CAD [26]. These scales show that self-efficacy can be a powerful construct to investigate how students perceive their ability in a particular content area. Our study seeks to develop a self-efficacy scale to measure ME students' belief in their FEM/FEA abilities, complementing the existing collection of self-efficacy scales in engineering education.

Methods

Study Context and Participants

This study was conducted at a large, public, 4-year institution in the Midatlantic US with a large engineering program. Mechanical Engineering is one of the largest departments in the College of Engineering, with more than 1,400 undergraduate students (masked for review). ME students are provided with a software package that gives them access to several CAE packages, including ANSYS, Siemens Nx, and SolidWorks. ME students at this institution are not required to take a specific course on CAE, but there are CAD modules included in core courses throughout the first two years. A junior-year Mechanical Design course typically includes a short FEA unit, but not all instructors include the module in their teaching. For students interested in diving deeply into CAE, there are two upper-level technical electives that focus on CAD/CAM and FEM, respectively.

The participants in this study were current ME students with Junior rank or above. Students were recruited to take the survey via emails to Junior and Senior listservs and class announcements in Senior Design, the FEM elective, and the Junior-level Mechanical Design course. The survey sample was mostly men and White students, but minority demographics are similar to those of engineering students at the institution of data collection. A full demographic summary is provided in Table A1 in the Appendix.

Survey Development

The survey instrument employed in this study was developed by the authors for this context. The survey contains four primary sections: demographics, CAE exposure, FEM interest and utility, and FE self-efficacy. The entire survey is included in the appendix. The demographic section included questions to assess eligibility for inclusion in the study (e.g., consent, major, class year) and questions to help us understand the sample (e.g., gender, race/ethnicity). The CAE exposure section asked students about whether they had encountered CAE content in specific ME courses and extracurricular activities. We also asked some logistical questions specific to our institutional context that have been omitted from the appendix for anonymity purposes. Next, students rated their interest in learning about FEM/FEA and ranked contexts where they expected FEM knowledge to be useful. The final section consisted of an eight-item scale used to measure Finite Element self-efficacy (FESE). This scale was adapted from a 3D-modeling self-efficacy scale that was developed and validated with middle-school, high-school, and college students [26], [27]. Both authors edited the items collaboratively and iteratively to lend the best face-validity to the scale. The only item that was drastically changed was item seven. The final FESE scale included in the survey was as follows:

1. I feel that I am good at setting up FE simulations from a CAD model.
2. I have confidence in my ability to model real parts and load cases using FEA software.
3. I am confident enough in my FEM skill to help others with FE models.
4. I am good at finding creative ways to model parts and/or load cases with FEA.
5. I believe I have the talent to do well with FEM.
6. I feel comfortable using FEA software.
7. I can use my knowledge of FE theory to have confidence in the accuracy of my FEA simulation results.
8. I feel I can communicate the results of FE simulations to other peers.

The survey was administered online via QuestionPro software. All procedures for data collection were approved by the IRB at our institution.

Analysis

Three main types of quantitative method were used to analyze the four sections of the survey: descriptive statistics, exploratory factor analysis (EFA), and null hypothesis testing via ANCOVA.

Descriptive Statistics

Descriptive statistics were used throughout analysis and were the main form of analysis for the first two sections, CAE exposure and FEM interest. The arithmetic mean was used as the measure of central tendency, and standard deviation was used to measure variance. All descriptive statistics were calculated using Microsoft Excel.

Exploratory Factor Analysis

When employing a new survey scale, particularly for psychological constructs like self-efficacy, it is necessary to test the reliability and validity of the survey items. For a new scale in a new context, exploratory factor analysis (EFA) is an appropriate tool to explore the factor structure of a scale and eliminate items that do not correlate with the constructs of interest. The first step of EFA analysis is to verify that the sample is sufficient to perform EFA. All MSA values in the Kaiser-Meyer-Olkin test of sampling adequacy were above 0.8, which indicates a reasonably large sample [28]. Bartlett's Test of Sphericity was significant ($p<0.001$), indicating that the correlations between items are large enough for factor analysis.

After verifying that EFA was possible with our sample, we used Jasp software [29] to identify the appropriate number of factors and items for the FESE scale. Kaiser's criterion, which specifies that factors with eigenvalues larger than one should be retained, was followed to determine the number of factors. To evaluate the overall fit of the factor model, both fit indices and error approximations were used. The Tucker-Lewis Index (TLI) and Comparative Fit Index (CFI) were examined to determine whether the factor correlations were better than random, with values above 0.9 indicating good fit [30]. To evaluate discrepancy between the model and the data, RMSEA was used, with values below 0.05 indicating good fit [28]. Cronbach's alpha was the primary measure of reliability for the scale, and 0.7 was set as the lowest value cutoff for sufficient reliability [31]. When removing items from the scale to improve fit, residual variance was used as a measure of misalignment with the scale. Throughout EFA, we ensured that the coherence and purpose of the FESE scale were maintained. In other words, items that addressed key facets of FEM were not removed, even if the fit measures suggested the change.

Null Hypothesis Testing

To answer our third research question, we compared the self-efficacy results across several demographic groups. The scores from individual items of the FESE scale were averaged to create an overall FE self-efficacy score [32]. Comparing the distributions between different groups is the purpose of Null Hypothesis Testing, so these tests were employed to analyze FESE scores. Because we wanted to test the effect of multiple demographic factors on one dependent variable (FESE scale scores), the Analysis of Covariance (ANCOVA) was appropriate [33]. For each analysis, assumptions were verified using Levene's test and Q-Q plots [33]. Complementary to the FESE analysis was a comparison of FEM theory and FEA software competency scores. A Wilcoxon Signed Rank test was used to compare the distribution of the two competency scores. When results from these tests were significant, effect sizes were reported to better contextualize the magnitude of the significant effect.

Findings

Analysis of the student survey data was completed with descriptive statistics and hypothesis testing. The following section outlines the findings from each major section of the survey.

CAE Exposure

The first section of the survey asked students about their encounters with computer-aided engineering (CAE) content throughout their undergraduate education. Our objective within this section was to identify when students first encountered different forms of CAE content and how frequently they returned to these topics. Recognizing that students develop engineering skills inside and outside the classroom, we asked participants about their CAE exposure from the curriculum and extracurricular activities.

Curricular Exposure

While there are standard procedures and course content for the mechanical engineering courses at our university, we did not assume that all students have the same experience in these courses. Exposure to CAE tools is one element of the curriculum that can vary depending on the instructor, semester, and licensing agreements. As such, we asked students to select all of the courses where they completed an assignment or project with CAD, CAM, CFD, or FEA. To generalize the courses for applicability to other institutions, we grouped them by level (i.e. class year when typically taken) and core/elective. Table 1 shows the distribution of students' first exposure to CAE content.

Table 1. Frequency of Students' First Exposure to CAE Content by Class Type

	CAD	CAM	CFD	FEA
First-Year	63	1	1	2
Junior Year Core	10	5	8	32
Senior Year Core	0	5	6	17
Upper-Level Electives	0	2	1	6
No Exposure	2	62	59	18

Based on Table 1, most students had been exposed to CAD tools during their first year. At our university, CAD training is a large portion of the first-year engineering curriculum, so this is expected. A majority of students had not had any exposure to CAM and CFD, while about two-thirds of survey respondents had experience with FEA. Most students who had experience with FEA were first exposed to this content during their junior year core courses. This aligns with the intended content in our junior-level Mechanical Design course. It is interesting to note that a few students had experiences in CAM and CFD in junior and senior-level courses, while most did not.

Most students were first exposed to FEA/FEM through coursework in college, but a few survey respondents had experiences outside the classroom. Five students responded that they first encountered FEM before college, likely in high school. Two students first learned about FEM through extracurricular activities, and one student was exposed through a work experience. While a minority, the experiences of these students reinforce the importance of investigating the skills and knowledge students gain outside of the classroom.

In addition to identifying students' first exposure to CAE content and tools, we were curious how often students encountered this content. Since our curriculum does not have a core course dedicated to CAE, learning is distributed throughout many courses. Theoretically, students build upon the knowledge of previous classes in each new encounter with CAE content. To measure the number of times a student had encountered CAE content, we counted the number of courses they selected as containing CAE content (the maximum possible count was eight). Figure 1 shows the distribution of student exposures. The boxplots in the figure mimic trends seen above in the first exposure table (Table 1). CAD and FEA, on average, have many more curricular exposures than CAM and CFD. While difficult to tell from the figure, the average number of curricular exposures to CAM was 0.21 and 0.32 for CFD. The maximum number of curricular experiences a student had with any type of CAE was six with CAD, and the minimum was zero for all four types of CAE. This distribution of curricular touchpoints exhibits notable differences between students despite taking the same core ME courses.

Extracurricular Exposure

As noted in Table 1 in the preceding section, some students are first exposed to CAE tools and knowledge through extracurricular activities. Furthermore, students can build upon their coursework by engaging in many types of out-of-class activity. This kind of exposure to CAE tools was captured in our survey in a similar manner to curricular exposure. Table 2 below shows the percent of responding students (not all participants completed this portion of the survey) who indicated exposure to CAE tools in their extracurricular activities. Competition Design Teams (e.g., FSAE, Concrete Canoe, Shell EcoChallenge), Work Experience (e.g., internship, co-op, campus job), and Personal Interest/Hobby are three activities with high frequencies of CAE exposure. CAD is the most common for all activities but highest for students with personal interest projects or hobbies. Competition design teams had the highest occurrence of CAM exposure, likely because teams manufacture many of their own parts. CFD exposure was the least common among CAE types, but Competition teams were again the highest in percentage (8.9% of respondents). For FEA, work experiences had the highest percentage of positive responses, with 17.8% of students saying that they were exposed to FEA at work. This corroborates the existing evidence that FEM/FEA competency is a valuable skill in industry.

Table 2. Frequency of Student Exposure to CAE Content in Extracurricular Contexts

	CAD	**CAM**	**CFD**	**FEA**
Competition Design Team	51.1% (23)	11.1% (5)	8.9% (4)	13.3% (6)
Engineering Club	11.1% (5)	2.2% (1)	0%	0%
Research	15.6% (7)	2.2% (1)	2.2% (1)	2.2% (1)
Work Experience	55.6% (25)	8.9% (4)	4.4% (2)	17.8% (8)
Personal Interest/Hobby	71.1% (32)	8.9% (4)	4.4% (2)	11.1% (5)
Non-ME Course	11.1% (5)	2.2% (1)	2.2% (1)	4.4% (2)

Following the same structure as our analysis of curricular exposures, we quantified the total number of extracurricular exposures to CAE content per student. The distribution separated by type of CAE is displayed in Figure 2. The patterns in this distribution are very similar to curricular exposure, with CAD and FEA having a wider distribution and higher average exposure count. Given the variety of extracurricular activities that engineering students can engage in, a wide range of CAE expertise and exposure is not surprising.

Overall, the data from the CAE exposure section of the student survey show that students are most often and first exposed to CAD. Other types of CAE tools typically follow later, and are much less common. In our sample, FEA exposure was more common than CFD or CAM, but still less common than CAD.

FEM Interest and Utility

The second section of the survey investigated students' interest in learning FEM/FEA and their desired use of the content once acquired. These questions were assessed via simple Likert response and ranking questions. To assess interest, we asked students to rate their interest in learning FEM/FEA compared to the average ME undergraduate student. The results are shown in Figure 3, and display a positive trend in FEM interest. More than 90% of students indicated that they were at least somewhat interested in developing their FEM skills and knowledge, which suggests that they are familiar with what FEM/FEA content is and see some future utility. It should be acknowledged, however, that this was marketed as a survey on students' FEM education experiences, which likely attracted students with a greater interest in FEM. It is possible that students with low interest did not complete the survey.

The second portion of this section provided students with seven environments where they could apply their FEM knowledge and skills. Students ranked the contexts where they expected their competency to be most useful. Figure 4 presents the proportion of each rank for all seven contexts. The contexts are arranged left to right from lowest average rank (Career) to highest (Technical Electives). More than 60% of students ranked their career as the place where their FEM competency will be most useful. The next two most popular contexts, Marketable Skills and Internship/Co-op, are also related to professional environments.

We defined marketable skills as the skills students would highlight on their resume and in job interviews. Clearly, students are thinking about how FEM competency will be needed in the workplace. Capstone and extracurriculars were often ranked in the middle (3-5), perhaps because we surveyed juniors and seniors that are career focused. Graduate school and electives were the lowest ranked contexts, likely because of low interest in those activities. A small number of undergraduates are planning to go to graduate school, so this context is not relevant to many students. Fourth- or fifth-year students have likely taken most or all of their electives, so this may also be a context that was not applicable for some survey respondents.

The findings in this section show that, in our sample, students are interested in learning about FEM/FEA and see it as useful in their future careers. Students hope to use FEM competency to get hired and to complete professional engineering work.

FEM Self-Efficacy and Competence

The third section of the survey collected data on students' Finite Element Self-Efficacy (FESE) using the eight-item scale and perceived competence with FEM theory and FEA software. Because this is a newly adapted survey scale, the first subsection will detail the statistical validation of the scale with Exploratory Factor Analysis. This is followed by statistical analysis of the self-efficacy data and the competency data.

Figure 1. Distribution of Curricular Exposures to CAE Content

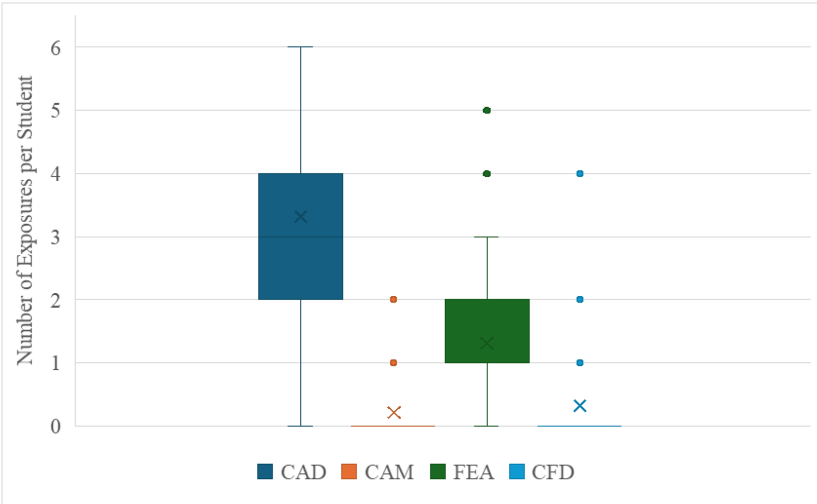


Figure 2. Distribution of Extracurricular Exposures to CAE

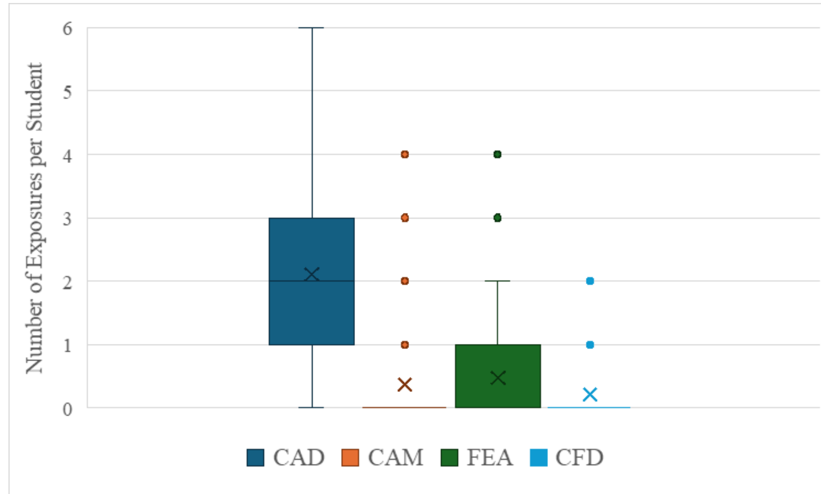


Figure 3. Interest in Developing FEM Competency

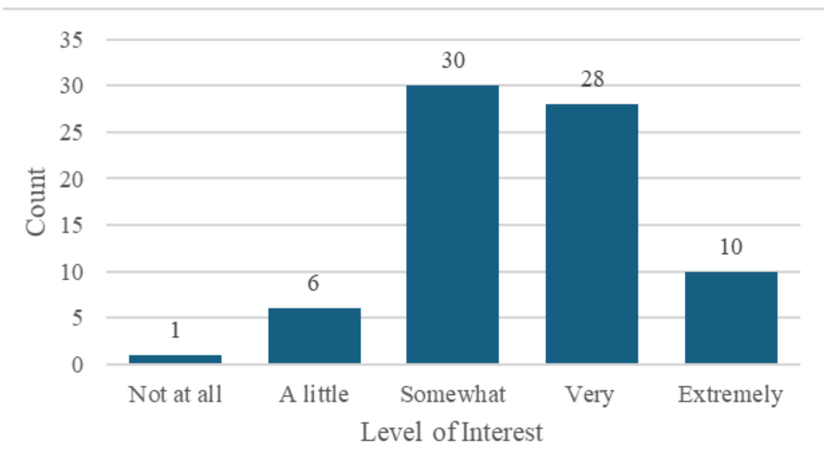
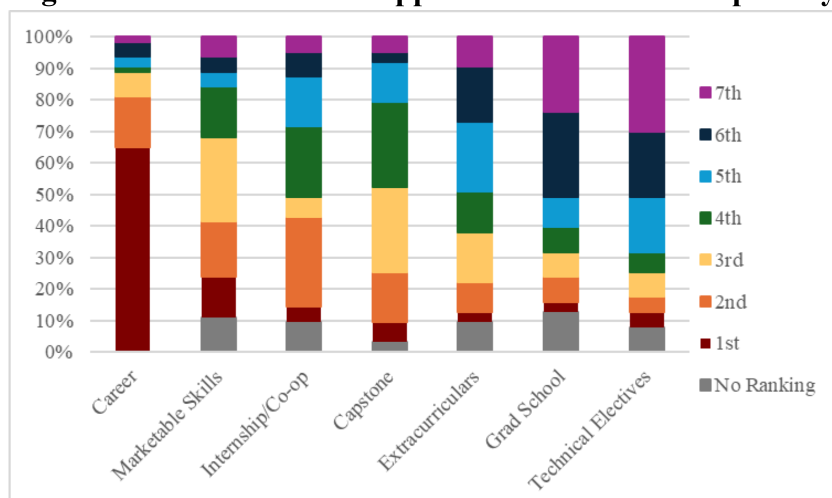


Figure 4. Student Ranked Applications of FEM Competency



Self-Efficacy Scale Validation

The validation of the FESE took place in three stages: assessment of the original scale, revision via EFA, and validation with measures of reliability and validity. Because this scale is an adapted version of a validated CAD self-efficacy scale [26], we were reasonably confident that our wording changes would not dramatically change the reliability of the scale. However, it is necessary to test our assumptions before analyzing the findings from the data set.

In the first stage of validity analysis, we verified that all eight items contributed to one factor using a Scree plot and eigenvalues. Both the Scree plot (see Appendix) and eigenvalues suggested that one factor was appropriate. We next analyzed the reliability and fit of the original scale with all eight items. While all factor loadings were larger than 0.6, Cronbach's alpha was high (0.936), and fit indices were approaching the 0.9 value (see Table 3), the RMSEA was very high for the original scale (0.214). An RMSEA above 0.1 suggests a significant problem within the factor model. Because of the concern caused by RMSEA, we decided to explore removing items from the scale in stage two.

Stage two of our validation analysis consisted of an iterative process of testing factors with fewer items. Best practices of Exploratory Factor Analysis were followed when testing combinations of items. We utilized the residual variances of each item to identify items that may be detracting from the fit of the model. Items were removed one at a time and replaced if the fit did not change or worsened. Ultimately, the model fit was significantly improved when items 1, 5, 6, and 7 were removed. The resulting 4-item scale (items 2, 3, 4 and 8) was the focus of stage three: revised validation.

Removing half of the items from our FESE scale was not taken lightly. We examined both the statistical evidence that the revised scale was an appropriate model (Table 3) and utilized our subject-matter expertise to assess whether the remaining items still captured all important elements of finite element knowledge and skill. The measures of fit and reliability were excellent for the revised model, so our primary concern was whether the scale was still conceptually sound. The remaining items address individual and collaborative FEM work, translating real world designs into FEM cases, and communicating analysis results (the Methods section presents the text of each item). The removed items address related concepts that are tangential to FEM/FEA practice rather than central. We agreed to remove items 1, 5, and 6. Item 7, however, addresses the important relationship between FEM theory and interpreting analysis results. It is unclear whether students' FEM theory self-efficacy is well represented in the revised scale. Alternative items and more commentary on this issue are addressed in the discussion. For the analysis in this paper, the revised scale with four items was used. The scores from each item were averaged to calculate an overall FESE score for each respondent.

Table 3. Reliability and Fit Measures for Original and Revised FESE Scales

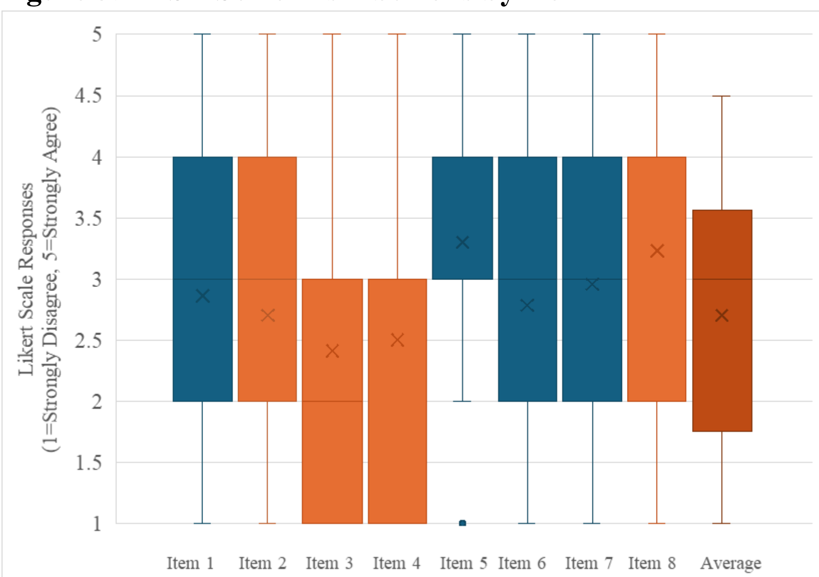
Version	Items	Cronbach's a	CFI	TLI	RMSEA	AVE
Original	1-8	0.936	0.872	0.821	0.214	0.653
Revised	2, 3, 4, 8	0.903	0.999	0.996	0.040	0.708

Note: CFI= Comparative Fit Index; TLI= Tucker-Lewis Index, RMSEA= Root Mean Standard Error Approximation; AVE= Average Variance Extracted

Self-Efficacy Analysis

Thanks to the validity improvements of the revised FESE scale, we were able to analyze the survey responses. We were first curious about the overall distribution of responses for each item and the revised average score (Figure 5). The box plots in blue show items that were removed from the overall average, and orange box plots show items included in the overall average score. Most items are centered around the middle (score of 3), which shows an even distribution of agreement and disagreement. Items three and four have a lower distribution, which shows more disagreement with the statements than agreement. Contrarily, item five shows more agreement than disagreement. The median of the overall average is in the middle at three, but the mean trends lower ($\bar{x}$=2.66).

Figure 5. FESE Scale Distributions by Item



Beyond descriptive statistics, we were interested in understanding how FESE might vary based on class year, previous FEM/FEA exposure, and perceived competency. An ANCOVA was used to identify any significant differences in FESE average score based on these characteristics. The results are captured in Table 4. The only significant result was Software Competency, meaning there was a significant increase in FE self-efficacy as a students' perceived competency with FEA software increased. The effect size is moderate (0.337), showing a decently strong relationship between these two measures. It makes sense that students who think they are more competent would also have a higher self-efficacy. Another interesting, although not significant, finding from the ANCOVA was the interaction between class year and FEA exposure. For this test, FEA exposure was broken into a high (more than 2 curricular exposures) or low (two or less curricular exposures). While class year and FEA exposure were not close to statistically significant by themselves, their interaction was nearly significant at the 5% level (p=0.075). This result can likely be explained by the fact that students in higher class years have taken more courses, and therefore have more chances to encounter FEA.

Table 4. ANCOVA Results for FE Self-Efficacy Scale

Variable	Sum of Squares	df	F-statistic	P-value	Effect Size (η^2)
Class Year	0.073	2	0.083	0.920	
High/Low FEA Exposure	0.192	1	0.435	0.512	
Class Year*FEA Exposure	2.377	2	2.697	0.075	
Software Competency	27.204	1	61.724	<0.001***	0.337
Theory Competency	1.007	1	2.285	0.135	
Residuals	29.089	66			

****denotes a significant result at 5% significance level*

FEM Competency

The final two questions in this section asked students, "Compared to the average ME Senior, how would you describe your skill level with [FEA programs/FE background and theory]?" The response to the first question is referred to as a students' FEA Software Competency, and the response to the second question is their FEM Theory Competency. The response options for these questions were a six-item scale from 0=No experience to 5=Expert. When analyzing the competency scores, we were particularly interested in variance by class year (Table 5).

Table 5. FEM Competency by Class Year

	Class Year	Mean	St. Dev.	n
FEM Theory	**All**	**3.15**	**1.26**	**74**
	3rd	2.92	1.32	13
	4th	3.38	1.27	47
	5th+	2.54	0.97	13
FEA Software	**All**	**2.88**	**1.31**	**74**
	3rd	2.08	1.19	13
	4th	3.23	1.29	48
	5th+	2.39	1.04	13

To compare whether there are significant differences between types of competency and class years, a Wilcoxon Signed Rank test and ANOVA were used. The Wilcoxon Signed Rank found that, for the entire sample, there was not a significant difference between theory and software competency (W=295.50, p=0.115). There was not a significant difference between class years for theory competency (F=2.631, p=0.079), but there was a significant difference between class years for software competency (F=5.703, p=0.005). Tukey post-hoc analysis showed a significant difference between software competency for students in the 3rd and 4th year (p=0.011). 3rd/5th year and 4th/5th year differences were not significant.

By analyzing FESE and FEM competency together, we are able to see how they are closely related. Students with higher perceived competency, typically older students, had higher self-efficacy. Students overall displayed agreement with most FESE scale items and rated themselves with intermediate FEM competency.

Discussion & Implications

RQ1: CAE Exposure

Our first research question asks, “where in their undergraduate experience do mechanical engineering students gain exposure to computer-aided engineering content?” The survey examined this question from both curricular and extracurricular perspectives and found similar trends for both. CAD was the most popular type of CAE by far, and students were introduced to CAD earliest. Most students in our sample were first exposed to CAD in their first year of college. The other types of CAE (CAM, CFD, FEA) lagged behind in number of exposures and time of first exposure. Students often did not interact with other types of CAE until their third or fourth year. The total number of exposures a student can accrue over their undergraduate education is inherently limited when they do not start until more than halfway through their degree. Introducing CAE tools later in the curriculum can limit opportunities for informal exposure (e.g., use in projects, extracurricular use, hobby/personal interest). Furthermore, students are often expected to utilize many types of CAE during their senior capstone projects. It is difficult for students to do this effectively if they have only been introduced to FEA or other CAE tools recently.

While most students were not exposed to CAM, CFD, and FEA in their coursework during the first two years, it is interesting to note that a small number of students did say they were exposed through coursework at these times. ME students are taking most of the same courses each year, so a natural question is how these students were working with CAE tools in their courses when most students were not. Projects or open-ended assignments in core ME courses and electives may provide an answer. It is possible that a few students took the initiative to learn some CAE tools for a project or assignment even when it was not required. This possibility aligns with our finding that most students are interested in learning more about FEM/FEA than they currently do through courses. High interest in CAE content could also explain some trends in extracurricular exposure. Students who participated in competition design teams and/or internships tended to have much broader exposure to CAE, including CAM and FEA, than other students. Students who are active in extracurricular engineering activities are responsible for real parts that need to be modeled, analyzed, and manufactured, so they are motivated to learn CAE content. Extracurriculars also provide an independent environment for students to try things without worrying about a grade. For these reasons, it makes sense why students with extracurricular experience would have more exposure to CAE.

Implications for Educators:

- Introducing CAE content early in the curriculum provides students more time to engage with informal learning in projects, extracurricular clubs, and internships.
- Some students may be independently learning CAE through course projects, but intentional integration into assignments spurs independent learning and exploration.
- Students with interest in developing CAE skills are seeking them out through extracurricular experiences, so access to tools/software outside of class is important.

RQ2: FEM Interest, Utility, and Competency
The second research question investigates how undergraduate ME students rate their interest in learning FEM and their competency with FEM theory and software. Interest in learning FEM was measured directly and indirectly through utility. Findings for both questions show students' strong interest in using FEM both as a student and a professional. It was affirming that more than 90% of students said they were interested in learning FEM content, but it is unclear whether students are interested in the theory and method or software competency. While not formally analyzed in this paper, anecdotal interviews with students completed by the first author and teaching experience from the second author suggest that students are more interested in learning how to use FEA software than the theory behind the software. This divide is also mentioned as a challenge in other papers by FEM educators [17], [18], [34]. Looking at perceived utility of FEM knowledge and skills, students are largely interested in the career implications of this competency. Most students rated their future career as the context in which FEM knowledge will be most useful. It is possible that students see software competency as a more tangible sign of their capabilities than more abstract theoretical knowledge. Connecting to the discussion on RQ1 above, extracurriculars were rated higher than electives on potential usefulness of FEM. This could reflect our institutional context where there are limited courses on FEM, or it could underscore the importance of extracurriculars as a learning environment for CAE skills.

The results from two questions on theory and software competency paint a slightly contradictory picture to the interest and utility results. For both competencies, the average score was about 3, which corresponds to an intermediate level. It was surprising that the mean score for FEA software competency was lower than the mean for FEM theory (although the difference was not statistically significant). Based on student interest, we expected the opposite trend. This could indicate that students do not get enough exposure to FEA software through coursework to feel competent or that they are reasonably proficient in many softwares but lack deep expertise in one. Future work could look more deeply into student competency ratings for both theory and software. It was also interesting that students in their fourth year (i.e. seniors) had the highest average competency. Students are most likely to take the FEM elective in their fourth year, so this could account for the difference between fourth and fifth year students.

Implications for Educators:
- Students are interested in FEM/FEA content and see it as useful for their careers.
- Connecting course content to jobs and internships is important to engage students, which could include using software that is common in industry.

RQ3: Finite Element Self-Efficacy
While our research question only addresses the extent to which students develop FE self-efficacy, our analysis included both the validation (and revision) of the FESE scale and statistical analysis of the survey results. Survey instrument development is inevitably an iterative back-and-forth between researcher expertise and the numerical results of EFA. Both the model fit and content validity are essential for a truly validated scale. As we revised the FESE scale, we identified problems with the original eight-item scale. The four items that were retained provide a parsimonious and statistically sound scale to measure students' FESE. While we believe that the choices made through our EFA validation process are sound, we are still hesitant about removing item seven, "I can use my knowledge of FE theory to have confidence in the accuracy

of my FEA simulation results." We believe that this item represents an important relationship between a students' theoretical FEM knowledge and the engineering judgment they exercise when interpreting FEA simulations. This relationship is not represented in any of the other scale items. However, we also believe that the wording and length of this item may have confused survey respondents. We hope to test alternate phrasing of item 7 in our future work and encourage other researchers to test other iterations of the FESE scale in their work.

The analysis of FESE results presents a few interesting directions for future study. While the survey scale is still in validation (confirmatory factor analysis should be used to revalidate in other contexts), the distribution of items suggests areas where students may feel less confident. The lowest average scores were on items three and four, which address students' confidence in helping others with FEM and finding creative ways to model parts, respectively. It makes sense that students would want to feel very comfortable with their own knowledge before helping others. Creativity is a skill that often comes with experience, so a student may feel that they have not had enough exposure to different parts or load cases to be creative with FEA. The highest average score was on item 5, which asked students whether they had the talent to do well with FEM. It is encouraging to see that most students agreed that they had the innate ability to succeed with this content. Connecting the ANCOVA results to the revised FESE scale, all four retained items in the scale reference FEA software. So, it makes sense that a student's perceived software competency would correlate with their FE self-efficacy score. The fact that software competency was the only significant predictor may also suggest that the current FESE scale is better at measuring a students' self-efficacy with FEA software than theoretical FEM content.

Implications for Educators:

- The FESE scale can be used as a tool to understand where your students are starting with FEM or to measure a difference over a FEM course or module.
- Students may feel less confident working with others on FEM content, so instructors can build opportunities for collaborative work into FEM coursework.
- Encouraging students to reflect on their abilities, accomplishments, and creativity can contribute to building their self-efficacy.

Conclusion

This exploratory study utilized quantitative methods to analyze an online survey of upper-level mechanical engineering students at a large, public university. The survey contained four sections that investigated the experiences and competencies students had with computer-aided engineering tools and the finite element method. The authors also developed a finite element self-efficacy (FESE) scale for undergraduate engineering students. The findings indicate that students encounter CAD much earlier than other types of CAE, but extracurricular participation can increase students' exposure. Students in the sample showed interest in learning more about FEM and using FEM/FEA in their future work experiences. Validation of the FESE scale via EFA led to a parsimonious, four-item scale. Recommendations to add a fifth item were proposed as future work. Overall, this study presented a broad account of how undergraduate ME students currently experience CAE and FEM education. Implications apply to ME departments and educators seeking to embed more CAE and/or FEM content into the undergraduate curriculum.

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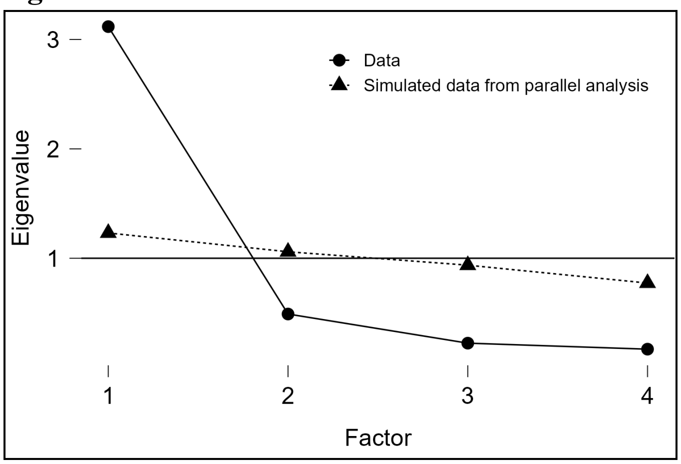
Appendix

Table A1. Participant Demographics

Class Year	Count (%)	Gender	Count (%)	Race/Ethnicity*	Count (%)
Third	14 (18.7)	Man	51 (68.0)	Asian	12 (16.0)
Fourth	48 (64.0)	Woman	21 (28.0)	African American/Black	2 (2.67)
More than Four	13 (17.3)	Other	3 (4.0)	Hispanic/Latino	3 (4.0)
				White	62 (82.7)

**Participants could select more than one option for Race/Ethnicity*

Figure A1. Scree Plot of Finite Element Self-Efficacy Scale



Appendix B. Survey Questions

Demographics

1. What is your class year?
   a. First Year
   b. Second Year
   c. Third Year
   d. Fourth Year
   e. Other (describe)
2. What is your gender?
   a. Man
   b. Woman
   c. Nonbinary

    d. Prefer not to say
    e. Other (describe)

3. What is your race/ethnicity?
    a. American Indian or Alaska Native
    b. Asian
    c. Black or African-American
    d. Native Hawaiian or Other Pacific Islander
    e. White
    f. Prefer Not to Say
    g. Other ____________________________

4. What is your major?
    a. ME
    b. ME & Other (describe below)
    c. Other (describe below)

FE Exposure

1. Where have you been exposed to Finite Element concepts and/or technology? Select all that apply.
    a. Before college
    b. First-year engineering
    c. ME Core Courses
    d. ME Technical Electives
    e. Senior Design
    f. Extracurriculars (e.g., design teams, personal projects, research)
    g. Internship/Co-Op
    h. I do not have experience with the Finite Element Method yet.
    i. Other (describe below)

2. [REDACTED]

3. [REDACTED]

4. Select the types of CAE tools you have used to complete an assignment or project in core ME courses. Check all that apply.

	CAD	CAM	FEA	CFD
[First Year Engineering Course]				
[Sophomore Course]				
[Junior ME Core Course]				
[Junior ME Core Course]				
[Junior ME Core Course]				
[Senior ME Core Course]				
[Senior Capstone]				
Technical Electives (any)				

5. Select the technical electives you have completed or are currently enrolled in.

   a. (Select from drop down menu)

6. Select the types of CAE tools you have used **outside of core ME courses**. Check all that apply.

	CAD	CAM	FEA	CFD
Competition Design Team (e.g. FSAE, BOLT, Solar Car)				
Engineering Club or Professional Society (e.g., ASME, eNable, Engineers without Borders)				
Undergraduate Research				
Internship/Co-op				
Personal Interests/Projects				
Courses outside of ME Core/Electives				

7. Which software brands have you used for CAD/CAM/FEA/CAE work? Select all that apply.

a. Ansys (Fluent, Mechanical, Discovery)

b. Autodesk (Fusion, Inventor, AutoCAD)

c. CATIA

d. Creo

e. OnShape

f. Siemens (Nx, ...)

g. Dassault Systems (SolidWorks, ...)

h. Other (describe)

8. In what context do you expect FEM skill will be most useful? Please rank.

a. Post-graduation Industry Career

b. Senior Design

c. Technical Electives

d. Extracurriculars/Design Teams

e. Internships/Co-ops

f. Graduate School

g. Marketable Skills (interviews, resume, grad school applications)

FE Competency

1. Compared to a peer in Mechanical Engineering, how interested are you in developing your FEM knowledge and skills?

a. 0 (Not at All Interested)- 5 (Extremely Interested)

2. Respond to each of the following statements: (Response: 1 (Strongly Disagree)-5 (Strongly Agree) Likert Scale)

a. I feel that I am good at setting up FE simulations from a CAD model.

b. I have confidence in my ability to model real parts and load cases using FEA software.

c. I am confident enough in my FEM skill to help others with FE models.

d. I am good at finding creative ways to model parts and/or load cases with FEA.

e. I believe I have the talent to do well with FEM.

f. I feel comfortable using FEA software.

g. I can use my knowledge of FE theory to have confidence in the accuracy of my FEA simulation results.

h. I feel I can communicate the results of FE simulations to other peers.

3. Compared to the average ME Senior, how would you describe your skill level with FEA programs?

a. 0 (no experience)

b. 1 (novice)

c. 2 (beginner)

d. 3 (intermediate)

e. 4 (proficient)

f. 5 (expert)

4. Compared to the average ME Senior, how would you describe your knowledge level with FE background and theory?

a. 0 (no experience)

b. 1 (novice)

c. 2 (beginner)

d. 3 (intermediate)

e. 4 (proficient)

f. 5 (expert)

Logistic Questions

1. Do you have anything else to share about your FEM learning experience? (Free Response)

2. Would you be willing to give additional clarification on your answers if needed? If you give permission for a student researcher to contact you, please put your email in the box below