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Balancing Theory, Programming, and Practical Application for Teaching of Finite Element Analysis Courses

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My primary teaching assignments in SUNY New Paltz are in the thermal-fluid areas such as Thermodynamics, Thermal System Designs, Fluid Dynamics, and Heat Transfer. As I believe in active learning, group activities in classroom and team projects are the two teaching tools that I utilize most to enhance students mastery on the subjects. Examples of team projects undertaken by students are designs of thermal devices and energy systems and projects inspired by contemporary scientific investigation.

My current research topics are motivated by improvement and innovation of engineering designs evolved in sustainable technology. Undergoing research projects include investigations of vortex-induced blade-less turbines and Tesla turbines for renewable energy applications, utilization of thermoelectric semiconductors for cooling, and research on supercritical carbon dioxide and refrigerants for green power generation. Relevant research interest includes numerical simulation of thermal-fluid interaction and biomimetic designs.

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Abstract

This study investigates the optimal combination of learning materials and teaching methods for a Finite Element Analysis (FEA) course within the Mechanical Engineering Program at SUNY New Paltz, New York. The challenge lies in balancing the teaching of FEA's mathematical theory and hand calculations, guiding students through basic FEA model programming, and training them in the use of commercial FEA software. Through student surveys, the study evaluates the effectiveness of various learning materials and pedagogical approaches. Findings indicate that while students recognize the importance of understanding the theoretical foundations of FEA, the complex mathematics involved presents significant challenges. Computer programming was identified as the most difficult aspect, whereas modeling with commercial software emerged as the most favored task. Despite some difficulties with teamwork, students expressed a strong preference for project-based learning and group work over individual study and traditional lecture-based approaches. The insights gained from this study provide a framework for structuring FEA courses to enhance critical skills, preparing engineering students for both academic and professional success.

Introduction

The foundation of FEA is the finite element method (FEM) which has its roots in the mid-20th century and has its foundational contributions from engineers like Richard Courant and Ray Clough. Initially developed for aerospace applications, FEM was designed to solve complex structural problems that were challenging to address using traditional methods. Over the years, thanks to the growth in computer power, FEM has grown in sophistication, becoming indispensable for various fields of engineering, from civil to mechanical and even biomedical applications [1]. Recent reviews have highlighted the diverse contributions of researchers like Turner, Argyris, and Zienkiewicz, marking the development of FEM into a comprehensive tool used across industries for solving complex engineering problems [2]. In the mechanical engineering industry, FEM is critical for optimizing design processes, enhancing efficiency, and improving product safety. Engineers rely on FEM to reduce costs, decrease prototyping time, and improve the reliability of designs across a wide range of applications, from automotive engineering to structural analysis [3]. As such, proficiency in FEM has become an essential skill for modern engineers.

Recognizing its significance, many undergraduate mechanical engineering programs have incorporated FEM into their curricula. Teaching methodologies vary across institutions, with some focusing on theoretical foundations, while others emphasize hands-on learning through commercial FEM software. The theory-oriented courses typically focus on the mathematical derivation of stiffness matrix, error estimation, and convergence of the solution. While courses that are application-oriented is geared toward equipping students with skills in computer simulation of physical problems demanded by industry. In terms of delivery, instructors often blend traditional lectures with practical exercises using tools like ANSYS or MATLAB to ensure that students gain both theoretical knowledge and practical experience [4]. Many programs also integrate project-based learning to help students better understand how FEM is applied in real-world engineering scenarios [5]. Lately, full online asynchronous courses on the introduction of FEA have been emerging in various education platforms such as Coursera, LinkedIn Learning, and EdX.

Balancing the range of topics in a finite element analysis course requires thoughtful planning, especially with limited credits in the curriculum. The emphasis on practical applications over theoretical foundations is often influenced by the need to align with industry requirements. Lissenden et al. from Mechanical Engineering of Penn State reported that finding out a consensus from faculty, student, and industry on the optimum learning objectives of finite element course was very difficult. The following question is very typical during the planning of a finite element course: should the focus be given on writing codes, understanding finite element results, mastering commercial finite element software, or understanding the finite element method itself [6]. Watkins reported a curriculum change of the Finite Element Analysis (FEA) course at California State University Chico. The course initially focused heavily on theoretical methods such as the derivation of stiffness matrix from the governing equations using Galerkin method, with minimal instruction in commercial software. Students performed manual tasks, such as assembling stiffness matrices, using tools like Excel and MATLAB. However, feedback revealed that while students understood the theory, they struggled to apply FEA effectively using commercial software, a crucial skill for industry. In response, the course was redesigned to balance theory with practical software training, emphasizing the correct use of FEA tools, including understanding assumptions, limitations, and result validation [7]. Gellin from the Mechanical Engineering Technology program at Buffalo State College chose to focus on hands-on learning in a lab setting for teaching the undergraduate course, moving away from the traditional approach that primarily emphasizes the fundamental theory of the finite element method [8]. Baker from the University of Kentucky took a similar approach in his finite element course, offering a balanced curriculum that covered both static and dynamic structural system analysis, including nonlinear systems. Students used commercial software like ANSYS and MATLAB and were required to write programs for analyzing small systems. Through this course, students gained familiarity with numerical methods and appreciated how they could be applied to more complex real-world systems [9].

Project-based pedagogy seems to be the predominant teaching method for finite element analysis used by engineering faculty. Interestingly, this approach also attracts instructors to introduce the finite element method into various engineering courses, where it can be beneficial at different levels from freshmen to senior. For example, Chaphalkar and Blekhman introduced Finite Element Analysis (FEA) into Statics and Solid Mechanics course at Grand Valley State University. This early exposure to computer simulation tools aims to prepare students for the demands of modern industry. Students learn 1-D Bar and 2-D Truss elements and perform both hand calculations and FEA analyses using software like ANSYS and MATLAB. This approach reinforces their understanding of Statics and Solid Mechanics while providing practical experience with FEA tools. Very importantly, Chaphalkar and Blekhman emphasized the importance of understanding fundamental FEA techniques to become a "well educated" engineer, rather than just a "well trained" user of FEA tools [10]. Higbee and Miller reported another interesting effort to introduce finite element analysis through an iterative design project assigned in a 200-level introductory biomechanics course for second-year undergraduate biomedical engineering students of Purdue University, Indiana. The project involves CAD design of fracture fixation plates, structural analysis using ANSYS, and mechanical testing of 3d-printed design products [11]. Shaikh from Curtin University in Australia introduced finite element analysis in a senior level course Structural Engineering. Students recognized that the utilization of Strand7 software helped their understanding in FEA, especially for analysis of structural mechanics [12]. Similarly, Lissenden et al. proposed project-based approach with emphasis on linear Hookean materials and application on designs using PRO/MECHANICA. They assigned four (4) projects to cover frame elements, plane stress elements, axisymmetric elements, and three-dimensional solid elements [6]. Nevertheless, the finite element modeling was introduced to freshmen students at Villanova University as part of a hands-on multidisciplinary project-based course. Ural, the faculty instructor, argued that the early introduction is expected to foster engineering development and to enhance the readiness of the engineering students for future industry and graduate studies [13].

This paper explores the perspectives of mechanical engineering students on the implementation of project-based learning in the Introduction to Finite Element Analysis course at SUNY New Paltz. It begins with a brief overview of the course, followed by a description of the research methodology. The study is based on a survey covering course materials, project themes, challenges in group work, and student expectations for future course improvements. Survey results show a strong preference for project-based learning over traditional lectures followed by exams. Students recognized that team projects enhanced their learning, with many citing working with commercial software as their favorite aspect of the project tasks.

Course Overview and Structures

EGM 302: Introduction to Finite Element Analysis was introduced into the Mechanical Engineering curriculum at SUNY New Paltz in the fall semester of 2017. This three-credit core course was designed to expose students to the growing importance of computer simulation in research and engineering design. Initially, the course was delivered using traditional pedagogy, with lectures and quizzes, and a project to assess students' mastery of the material. The lecture content heavily relied on an online EdX course developed by Dr. Rajesh Bhaskaran from Cornell University, titled *A Hands-on Introduction to Engineering Simulations*. This course simplifies finite element analysis theory and emphasizes understanding the modeling process of physical problems and the post-processing of numerical results. Completing the EdX certification accounted for 60 percent of the final grade. The EdX instructional videos provided valuable examples for modeling and simulating physical problems using ANSYS Workbench, which supported the hands-on projects assigned to students. The expected learning outcome was for students to demonstrate the ability to set up, analyze, and post-process an engineering problem using commercial analysis software. These outcomes aligned well with ABET's requirement for students to demonstrate 'an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

In the fall 2018 and 2019 semesters, further development of the course incorporated both team and individual projects, as well as computer programming using MATLAB by MathWorks. The course content was guided by chapters from the 4th edition of *Finite Element Analysis: Theory and Application with ANSYS* by Saeed Moaveni. This textbook was chosen for its clear, step-by-step FEM calculation examples for elements with varying degrees of freedom (DOF) and its accessible mathematical derivations of the element stiffness matrix, which are well-suited for undergraduate engineering students. However, the ANSYS examples in the book were less applicable to our course, as they focused on ANSYS APDL (ANSYS Parametric Design Language) rather than ANSYS Workbench.

To cover FEA coding in MATLAB—content not available in the textbook—class instruction became the primary teaching method. Quizzes and in-class activities were added to reinforce learning of both the finite element procedure through programming and computer simulations using ANSYS Workbench. Team projects were assigned to explore various mechanical engineering problems and physical phenomena. The EdX online course was retained as a companion resource, accessible throughout the semester. Custom instructional videos on ANSYS modeling and Matlab coding were developed and then published in the learning management system (LMS) Blakcboard to help students in their homework and projects.

The mathematical foundation of FEM was presented in a simplified manner, focusing on the relationship between shape functions and the stiffness matrix. The finite element method was demonstrated step by step, alongside its implementation in MATLAB. Introducing MATLAB programming helped students grasp how finite element models are processed in a computational environment. Understanding the algorithm was expected to help students recognize the importance of avoiding potential errors when working with computer models. The Direct Method, due to its simplicity, was used to introduce the key concept of discretization, which is central to the FEM.

The computer programming of FEM was focused on simple structural elements such as one-dimensional spring, two-dimensional trusses, beams, and frames. In the fall semesters of 2018 and 2019, a brief coding material on two-dimensional plane elements such as plane stress and plane strain was presented as well. The idea of showing various elements was to show that the numerical protocols in FEM are typical, which generally involves calculation of local stiffness matrix, necessary transformation of coordinate systems, assembly of the global stiffness matrix, application of boundary conditions that lead to reduction of stiffness matrix, and finally solving the unknown displacement vector and reaction vector. Furthermore, coding examples of one-dimensional heat and fluid problems as well as simple structural dynamic problems were provided to demonstrate capabilities of FEM beyond structural static mechanics.

The use of commercial software packages in the teaching was essential in demonstrating the application of the Finite Element Method (FEM) to solve complex three-dimensional geometries, multi-body interactions, and various physics (such as thermal stresses). It also allowed for near-realistic boundary conditions and loads, as well as an exploration of how mesh refinement impacts solution convergence. The software's advanced graphic-user-interface (GUI) capabilities were useful for presenting results and, more importantly, teaching students how to interpret them correctly. Throughout the course, the importance of result verification using available analytical solution and empirical formulation was emphasized. Students were reminded that while the commercial tools are highly sophisticated, they focus only on ensuring the correctness of software inputs and do not guarantee the correctness of the model itself. The phrase 'Garbage In, Garbage Out' (GIGO) was frequently used to stress the importance of proper modeling, as the accuracy of the simulation outcomes relies heavily on the correctness of the model.

The commercial package ANSYS Workbench for Students [14] was utilized in teaching since the course was introduced in fall semester 2017 because this package was used in the online EdX course by Dr. Bhaskaran. Secondly, the software was included because its academic version allows 128,000 nodes/elements for structural analyses or 1 million cells/nodes for fluid physics (2024 R2 version) which is sufficiently large for education purposes.

In the 2019 fall semester, students were asked to work in teams for five (5) separate mini projects that cover trusses, beams, frames, heat transfer, two-dimensional planes and structural dynamic problems. The team up was particularly important to accelerate the learning process. The assigned projects specifically require students to analyze structural and heat problems using ANSYS and Matlab. Project assignments on computer programming were limited to two-dimensional truss, beam, frame, plane strain and plane stress elements and one-dimensional heat modeling. A simple two–dimensional harmonic modeling was included as an extension from the frame model. The ANSYS Workbench was utilized to study the effects of the third dimension, interacting bodies, and mesh refinement.

The team projects emphasize the following aspects:

1. Problem identification and modeling
2. Selection of elements, mesh refinement, and boundary conditions
3. Verification of results and correct interpretation of outcomes
4. Group learning and teamwork

The mini projects were assigned to strengthen students' mastery in using the finite element method and commercial software for solving near-realistic problems. In these projects, students are expected to use the newly acquired knowledge to solve problems motivated by real-world applications. The problems offered in the mini projects are relatively more complex than that given in the homework, but they were still categorized as simple due to the low number of degrees of freedom (DOFs). Here, students were also trained to perform problem identification which includes the selection of appropriate physics, simplification of geometries, materials, and boundary conditions.

The result verification is facilitated by analytical solutions learned in prerequisites such as Statics, Mechanics of Materials, and Fluid Dynamics. The FEA course, therefore, can be considered as an excellent review of past materials such as force and moment balances, deflections of beams, and Bernoulli equations. Furthermore, students realize the effects of high order elements and mesh refinement from comparing the results from Matlab codes and commercial software.

The individual project offered a unique opportunity for students to cultivate their creativity and synthesis skills. By tackling complex physical problems that piqued their interest, students were challenged to creatively simplify these challenges to accommodate the finite element technique they had acquired. The limitations imposed by the academic version of ANSYS Workbench further necessitated innovative problem-solving and critical evaluation. Aligned with Bloom's taxonomy, the course curriculum was designed to foster a comprehensive learning experience. As illustrated in Figure 1, various assignments, ranging from lectures and videos to quizzes and in-class activities, were strategically mapped to different levels of Bloom's taxonomy, from passive learning to higher-order thinking skills like reflection, synthesis, and creativity

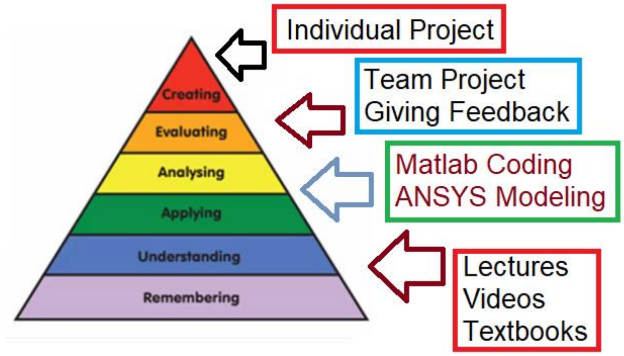

Figure 1 The relationship between course assignments and Bloom's learning levels

More importantly, students are expected to perform systematic strategy in using commercial software that consists of the pre-processing, processing, and post-processing stages. The pre-processing stage involves several aspects such as:

a. Problem identification that includes the selection of appropriate physics, simplification of geometries, and selection of materials
b. Geometry creation and setting up accurate boundary conditions
c. Selection of elements and evaluation of mesh refinement

When the commercial software is used, the processing stage is understood as a "black box" that would produce output based on the input. The warning and error messages during this stage serves as learning tools to increase mastery. Finally, the post-processing stage must involve verification of results using known analytical equations, accurate interpretation of results, summarizing the results and modeling for professional presentation through writing and presentation.

Method of Survey

The data on student's perspective of finite element learning was collected using Google form. Responses are collected anonymously from about 37 students registered in the fall semester of 2019. There are 29 questions and 20 of them are presented using the Likert scale. The remaining questions are either multiple choice or multi selection. Due to the high emphasis on project-based learning, many of the questions are relevant to the effects of the assigned team and individual projects on the learning and the teamwork skills. The given statements listed below (1-20) must be judged using Likert scale.

1. Working on projects has helped me understand better the importance of FEA in engineering design and analysis
2. Working on projects has developed my confidence on FE analysis
3. Working on projects has helped me in learning and understanding the calculation steps of FEM
4. Working on projects has helped me in mastering ANSYS as a tool for engineering analysis
5. Generally, project-based learning is the preferred method to study Finite Element Analysis
6. The traditional learning method with class instruction followed by homework and exams should not be used for Finite Element Analysis course
7. Mini Projects worked in the course are relevant to real-world applications

8. Mini team projects have stimulated me to learn more about ANSYS and FEA
9. Working in teams has made the learning process easy
10. The theoretical part of Finite Element method should not be discussed at all in this course
11. The computer programming of Finite Element method should not be included in this course
12. The Individual Project allows me to express my mastery on FEA and my creativity in solving complex engineering problem
13. The FEA course should be made technical elective
14. Development of team working skills should not be part in the course objective
15. In FEA course, students should be allowed to work individually on all projects
16. Working in teams allowed me to learn FE analysis effectively
17. Each student should be assigned to do a specific task on each project to make sure that no student will only do the same task on all projects
18. I have been doing the same task (only ANSYS modeling, only writing, etc.) for almost all of the mini projects
19. Random grouping has allowed me to meet and know more students - hence to grow my study group
20. Random grouping makes the team difficult to work as members do not know one another

The following questions (21 to 29) are asked as either multiple choice or multiple selection.

21. If I was asked to make a group for FEA projects, I can easily come up with a group of … (select only one)
22. In this course, I learn how to use ANSYS mostly from (select only one)
23. In this course, I learn how to code the FE method mostly from (select only one)
24. In the future, the number of mini projects should be (select only one)
25. The difficult issues of the teamwork are (you may select more than one)
26. The most difficult part of the course to learn is (select only one) …
27. When working on mini projects, I prefer to work with (select only one) …
28. My favorite task(s) in mini projects have been …
29. In the future, I would like to study FE simulation for the following topics (you may check more than one)

Results and Discussion

Questions 1 to13 are relevant to the teaching pedagogy of the course, particularly in terms of the project-based approach as well as the attempts to achieve collaborative learning through teamworking. Generally, students benefited from working on projects as it helps them understand the importance of FEA and mastering for engineering designs and analysis. Most students (about 83 percent) indicated that project-based learning, not the traditional pedagogy that involves mostly lectures and exams, is the preferred method to study FEA. The response distribution are shown in Figure 2 below. Moreover, about 65 percent of students also stated that working in teams has helped them learn finite element easily and effectively. However, about 19 to 24 percent of students felt neutral about it. While it looks surprising, the data somewhat agrees with 16 percent of students who preferred to learn the finite element method and ANSYS on their own through online video resources, textbooks, and class lectures.

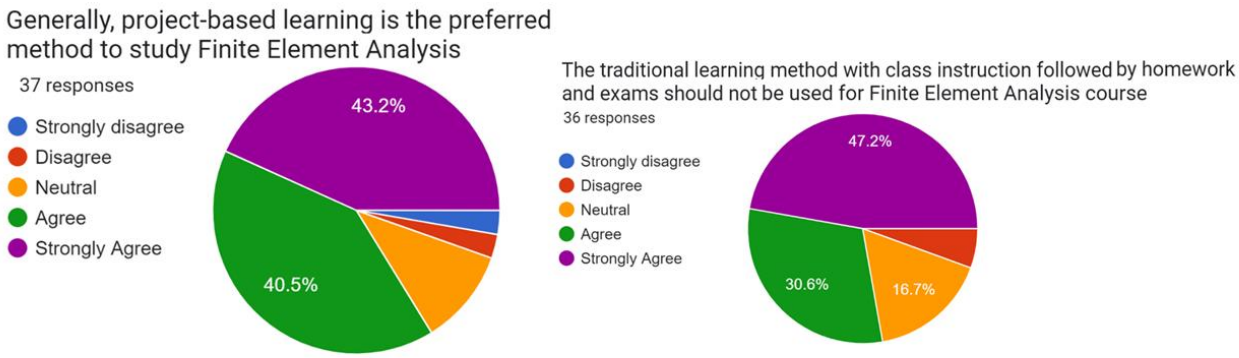

Figure 2 Most students agree and strongly agree that project-based learning is the preferred method for studying FEA and that the traditional method involving mostly lectures and exams should not be used

Regarding FEA learning materials, approximately 74% of students believed that theoretical concepts should continue to be studied, while around 22% remained neutral. This outcome was somewhat unexpected, as the theoretical aspects often involve fundamental FE mathematics, which can be abstract and overwhelming. However, in teaching this material, the emphasis was placed on practical understanding. Key topics included the difference between discrete (nodal) solutions and continuous solutions, the conceptual role of shape functions in linking nodal solutions to analytical ones, the types of elements and their degrees of freedom, and examples of physical phenomena represented by these elements. The relationship between the stiffness matrix, displacement vectors, and load vectors was also highlighted. The Direct Method, known for its simplicity, was used to illustrate how to derive the stiffness matrix for a one-dimensional spring element.

Approximately 60% of students identified the computer programming aspect of the finite element procedure as the most challenging material to learn. Despite this, opinions on whether to exclude computer programming from the course were fairly balanced across the five levels of the Likert scale, making this one of the most intriguing findings of the survey. About 24% of students strongly agreed that coding should not be included, while roughly 22% strongly disagreed. Another 24% of students were neutral on the matter. The pie charts below visually represent this distribution.

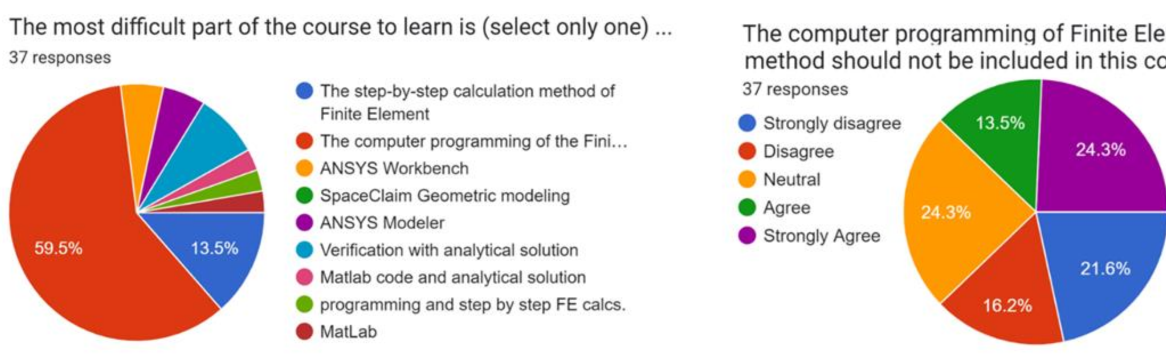

Figure 3 While 74% of students found computer programming and FEA calculations challenging, opinions were divided on whether to eliminate computer programming from the course.

The mixed responses may have resulted from the intensive MATLAB coding included in the FEA course during the 2018 and 2019 semesters. Following the guidance of the chosen textbook, the course covered increasingly complex elements, starting with simple 1D spring structures (1 degree of freedom per node) and advancing to 2D beams (2 degrees of freedom per node), 2D trusses (2 degrees of freedom per node with a rotational matrix), 2D frames (3 degrees of freedom per node, also with a rotational matrix), 1D heat transfer elements using line elements (1 degree of freedom per node), 2D plane stress and plane strain problems using linear triangular and rectangular elements (2 degrees of freedom per node for low mesh applications), and finally, 1D Newtonian laminar flow modeled with 1D fluid elements.

The inclusion of ANSYS modeling significantly enhances student engagement in learning. Despite its complex procedures, over 70% of students identified ANSYS modeling as their favorite project task. Additionally, more than 80% reported that working on these projects helped them develop skills in computer simulation. Notably, only about 24% of students relied on instructors for guidance in using ANSYS. Instead, students learned how to use the software primarily through peer collaboration, online video resources, and self-study. The chart shows that 16 percent of students learn how to model in ANSYS from their teammates.

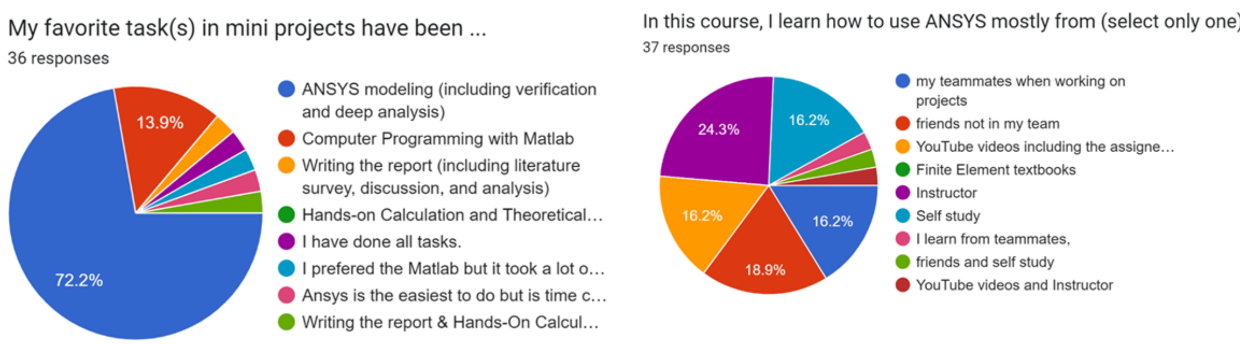

Figure 4 The charts clearly indicate that most students prefer working with commercial software on their projects. Additionally, students reported using various learning resources to master the software. Interestingly, about 14% of students also expressed an interest in computer programming.

Regarding the project themes, most students felt that the assignments adequately reflected real-world applications, although about 16% remained neutral. The projects ranged from designing simple 2D truss, beam, and frame models to analyzing stress concentration in plates with holes under plane stress and solving steady heat conduction problems. Students overwhelmingly agreed that these projects motivated them to learn more about ANSYS and computer simulations. When asked about showcasing creativity and mastering simulations in individual projects, 43% of students agreed or strongly agreed that this could be achieved, though, surprisingly, a similar percentage felt neutral. The independent project allowed students to work on topics of personal interest, with many choosing their senior design capstone projects, while others focused on independent research. Students were encouraged to propose real-world physical problems of interest, and then develop both two-dimensional models and simplified three-dimensional representations, focusing on either structural or thermal aspects.

Questions 14 to 21 explore the impact of teamwork on learning. Approximately 73% of students disagreed or strongly disagreed with the idea of removing the development of teamwork skills through team projects from the course. Additionally, only about 24.3% of students agreed that they should be allowed to work individually on all projects, rather than just one. These responses clearly indicate strong preference toward group learning. Responses regarding the assignment of different tasks to students on various projects were mixed and nearly uniformly distributed, with 35% of students favoring the idea. When asked about performing the same task on each project, 43% agreed or strongly agreed, while 52% disagreed or strongly disagreed. The response simply indicates that students were trying their best to be effective in both learning and finishing the projects. Concerning the random selection of team members, more than 50% of students felt that this approach facilitated the growth of their collaborative study groups. However, a similar percentage also noted that random grouping created challenges for effective teamwork. Despite this, over 65% of students expressed confidence in their ability to form groups of 3 to 7 members, which can be further improved. Lastly, approximately 57% of students recommended reducing the number of projects from five to a range between one and five, while around 41% suggested shortening the report.

Course Improvement

Based on feedback from the 2019 course evaluation, the curriculum was adjusted to prioritize content and team projects. While computer programming initially focused on 2D truss, beam, and frame elements, the development of 2D plane elements, involving Jacobian transformation and Gauss-Legendre numerical integration, was discontinued. To address problems commonly modeled as 2D planes, such as plane stress, plane strain, 2D heat transfer, and 2D fluid mechanics, students utilized commercial software like ANSYS. Additionally, since fall 2021, another commercial software – LISA FEA – [15] has been added into the course materials. The finite element software is developed in Canada, and it offers a free version with very limited node numbers up to 1300 nodes for educational usage. Despite its small size, the software has been considered as a good teaching tool for FEA. Its simple modeling graphical user interface (GUI) allows students to easily select elements needed for mesh refinement analysis. Furthermore, the number of team projects dropped to four (4) in 2020 and further reduced to three (3) team projects from 2021 to now. The independent project has been kept in the module and students were given opportunities to exchange constructive feedback.

Conclusion

In conclusion, project-based learning, incorporating both team and individual assignments, is the preferred method for the Introduction to Finite Element Analysis course. Students reported that they find it easier to learn through project work and collaborative study. The survey also highlighted the need to include fundamental theories of finite element analysis and computer programming. Despite the complex steps involved, students indicated that working with commercial software for computer simulations was their favorite task. Moreover, most students agreed that real-world projects motivated them to learn about computer simulations and their significance in engineering design and analysis.

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