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Integration of Digital Tools for Engineering Design, Analysis and Optimization

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Abstract

With the rapid advancement of digital technologies and computational resources, computer aided design and engineering tools have been widely used to improve efficiency while reducing time to find engineering solutions to complex systems. While industry adapts itself to fast-evolving technologies, engineering curricula need to be constantly updated, not only to keep up with new technologies, but also to educate and train engineers that are better prepared to enter the workforce. This paper outlines the development and inclusion of Computer Aided Engineering (CAE) in an undergraduate curriculum in Mechanical Engineering at a Historically Black University. The course prepares students to design complex systems using advanced CAD, and trains them to be proficient in engineering analysis tools using Finite Element Analysis and Computational Fluid Dynamics. Furthermore, students learn to optimize complex structures using a revolutionary design method called Generative Design. Integration of advanced CAD, FEA, CFD and optimization provide students with hands-on skills, teach them how to work on Multiphysics design projects in a team through synchronous and asynchronous communication tools, and better prepares them for departmental capstone design series coursework, as well as, numerous technical electives.

Introduction

Computer aided design (CAD) tools, along with engineering analysis software for finite element analysis (FEA) and computational fluid dynamics (CFD) have been increasingly advancing over the last several decades. These advancements are occurring not only because of ever-increasing performance of personal and parallel computing capabilities, but also because there is increasing demand for innovative approaches to complex multi-physics problems. Additionally, improvements in commercial software products have led to more user-friendly interfaces, which allow advanced solid modeling and prototyping tools to be used as early as freshman year in engineering programs. Likewise, while FEA and CFD previously required an advanced degree to develop the expertise to properly implement, not too long ago, such engineering analysis software tools are now being widely used even at the undergraduate level. However, while commercial software is now more advanced and user-friendly with additional physics and capabilities, performing advanced engineering analysis does still require some level of extensive training of, along with associated understanding of engineering fundamentals for proper interpretation of results from running complex engineering problems.

The need for inclusion of technologically advanced tools within innovative curricula to prepare the next generation of engineers is important, so that future engineers are better prepared for the ever-demanding and competitive workforce in this era of globalization, with experience and expertise in using up-to-date technologies and skills. However, while it is important to make adjustments to curricula to reach such ends, the demand for lower number of engineering credits (e.g. 120-credit curriculum) must also be considered, as the cost of higher education and the importance of four-year graduation rates are as equally important as preparation of well-rounded engineers.

Integration of CAD, FEA, and CFD as separate courses in undergraduate curricula or as part of fundamental core courses (e.g. fluid mechanics, solid mechanics) is commonly known [1-3].

Especially CAD is widely accepted as a core course in many undergraduate engineering curricula. On the other hand, FEA and CFD are offered either as electives or as a component of other common courses such as fluid mechanics and solid mechanics, to expose students to such tools and software early on. However, integration of design and engineering analysis techniques under one core course is not a common approach, especially at the undergraduate level. Thus, this paper will discuss a recently developed junior-level core course, Computer Aided Engineering, and its implementation into an undergraduate curriculum, which includes integration of advanced CAD and engineering analysis tools for FEA and CFD, along with Generative Design, a revolutionary optimization technique. Surveys, learning outcomes, and student self-assessments of this course are also presented in this work.

Motivation for Digital Tools in Engineering Curricula

The main motivation of the integration of basic and advanced design and analysis tools in engineering curricula is to train/educate students with up-to-date technological software/hardware to become industry-ready engineers for the workforce. While achieving this goal, such integration allows students to learn hands-on tools, to tackle real-world design problems with computational resources, and finally, to validate findings against back-of-the envelope calculations based on fundamental knowledge learned in basic core courses.

At Howard University, a 120-credit Mechanical Engineering curriculum offers traditional core courses, as well as, elective courses based on four specialty areas including energy, applied mechanics, aerospace and manufacturing/design. In response to demands from various constituents, a new core course, Computer Aided Engineering, was recently added to the curriculum in order to teach students advanced design (CAD) and engineering analysis tools (FEA and CFD), to increase their skills in upper level courses such as a capstone design series, and to prepare better and more competitive students for engineering practice and the national/international engineering workforce.

Computer Aided Engineering: A Hands-On Course for Engineering Design, Optimization and Analysis

Computer Aided Engineering (CAE) is a core course taught at the junior level. Due to its objectives, the course has three pre-requisites: Introduction to Computer Aided Design, Solid Mechanics and Fluid Mechanics I. CAE, which trains students and teaches commercially available software for multidisciplinary design and optimization, is divided into four subsections: CAD, FEA, CFD and Topological Optimization/Generative Design. With the technical skills gained in class, students virtually solve complex engineering design problems using CAD, FEA and CFD software (i.e. Fusion 360, Autodesk CFD). The course covers generative design, shape optimization, stress analysis and fluid-thermal system design with practical engineering problems. In the time of Covid-19, students worked on multiphysics design projects in teams through offline meetings and synchronous/asynchronous communication platforms such as Slack and Blackboard.

As mentioned previously, introductory CAD is often taught at the freshman level, but this CAE class involves CAD at advanced levels with the inclusion of shape optimization tools and a revolutionary design method called Generative Design for complex design scenarios and engineering analysis. Students use basics of fluid-thermal sciences and solid mechanics for back-of-the-envelope calculations, learn stress/flow analysis software tools for FEA and CFD simulations, and validate computational results against basic calculations. It allows students to gain not only important software skills but also learn validation and verification (V&V) by tackling real-world design problem for engineering practice. Details of course objectives are given immediately below, followed by a detailed explanation of the key subjects covered in each module, along with results of surveying students on their experience in the course, presented module-by-module.

Course Objectives

- Students will understand basic fundamentals of FEA (Finite Element Analysis) and how the method can be applied to solve engineering problems.
- Students will be able to formulate simulations for various engineering problems by building models, applying boundary conditions, mesh design, setting up the calculation, and displaying calculation results (i.e., solid mechanics, buckling analysis, fluid mechanics, modal analysis, thermal/thermal stress).
- Students will be able to use the topology optimization method to improve the existing mechanical design part in terms of cost and mass.
- Students will be able to understand the concept of the generative design for design optimization and use the method for engineering design.
- Students will be able to interpret the result from various simulations and use those to improve the design.

Module 1: CAD, Shape Optimization and Generative Design

Computer Aided Design is the first step of setting up a CFD or FEA simulation. As mentioned previously, students learn basics of CAD in the Intro to Computer Aided Design during their freshmen year. However, CAE exposes juniors to new drawing tools to widen their CAD knowledge, as well as, exposure to the native drawing tools found in each FEA and CFD software. Knowledge of 3D modeling tools is particularly important for interaction with FEA/CFD codes for engineering analysis, which typically requires multiple simulations for parametric solutions (i.e. “what-if” scenarios). The process exposes students to collaborate as a team via a cloud-based CAD software in preparation for group projects in the second half of the course. Figure 1 shows sample CAD projects which were built using Autodesk Fusion 360.

Figure 1. Sample CAD projects using Autodesk Fusion 360

One of the unique aspects of CAE is to expose students to shape optimization and automated design optimization based on shape or design constraints. Shape or topology optimization is an algorithmic process which provides the most efficient design solution based on a set of shape constraints by removing materials from the design. Shape optimization typically occurs near the end of the design process when a final product needs weight reduction and cost reduction due to materials [4]. Figure 2 shows the process for shape optimization which uses simulation technology to predict the design performance and automatically makes the changes to improve the design and accelerate product development processes.

Figure 2. A sample design project demonstrating shape (topology) optimization in Computer Aided Engineering

Generative design is a design exploration process available in Autodesk Fusion 360. A series of designs are generated in an iterative manner using a statistical method in conjunction with stress analysis, machining options, materials and other factors such as weight, cost and stiffness [5-6]. Generative design is different from topology (shape) optimization. Topology optimization starts with a fully defined CAD model and a mesh model must be rebuilt as valid geometry in a CAD system. In contrary, generative design in Fusion 360 holds out constraints, areas, loads and manufacturing process based on design requirements. As a result, shape optimization returns one outcome while generative design provides multiple CAD-ready solutions based on an iterative optimization process.

Figure 3 shows an example design process by Generative Design in detail [7]. Different from a regular design and analysis process, generative design starts with partial or no design model and inputs necessary boundary conditions (i.e. preserve and obstacle geometries, loads, materials, machining processes, and design objectives).

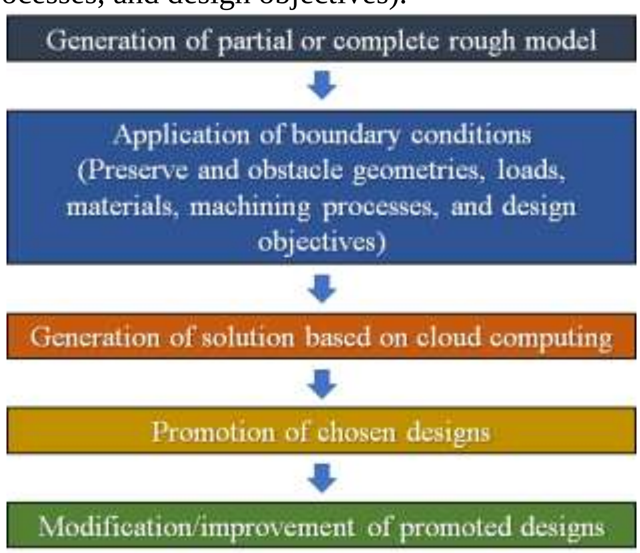

Figure 3. Design process based on Generative Design

Generative design is a novel design process for optimizing engineering parts. It calculates solutions based on materials, design specifications and objectives. After optimal solutions are obtained, the best design is chosen based on weight, cost of the design, stiffness or other design parameters. The chosen design can be modified or improved with additional constraints. Cloud-based computing is used because of the massive calculations and extensive computations associated with optimal solutions.

CAE course covers the above detailed theory and hands-on practice of generative design using Autodesk Fusion 360. The course covers the optimization tool in detail and teaches students how to get optimized solutions with respect to materials, machining processes, design requirements and objectives. The generative design tool offers students an innovative approach to design lighter and more cost-effective parts, which are much more efficient than parts by conventional design processes. Optimization of parts can easily be performed based on cost, strength and manufacturing processes. CAE teaches students this important tool combined with additive manufacturing so that students are industry-ready with this innovative technology when they enter the workforce. Figure 4 shows a part which was created by Autodesk Generative Design in CAE, based on multiple constraints of an assembly.

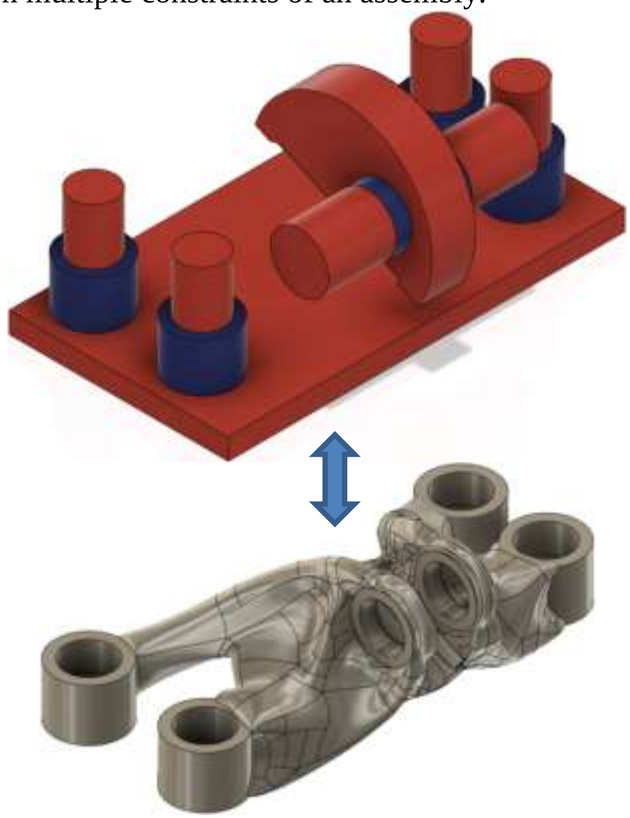

Figure 4. A sample project for Generative Design in Computer Aided Engineering

Figure 5 shows a part of the survey given to the students who took the CAE course in Spring 2020. Out of 29 students who took the course, 28 students participated in the survey. Survey results showed positive responses regarding CAD activities covered in class. Over 90% of the students were satisfied or extremely satisfied with all aspects of Module 1. Overall satisfaction with regard to CAD was 96%. All of the students were satisfied with the different components of Module 1.

<u>Question:</u> How satisfied are you with Module 1 (Fusion 360, Shape Optimization, Generative Design and CAD) and activities in increasing your skills for hands-on software use and engineering design/analysis?

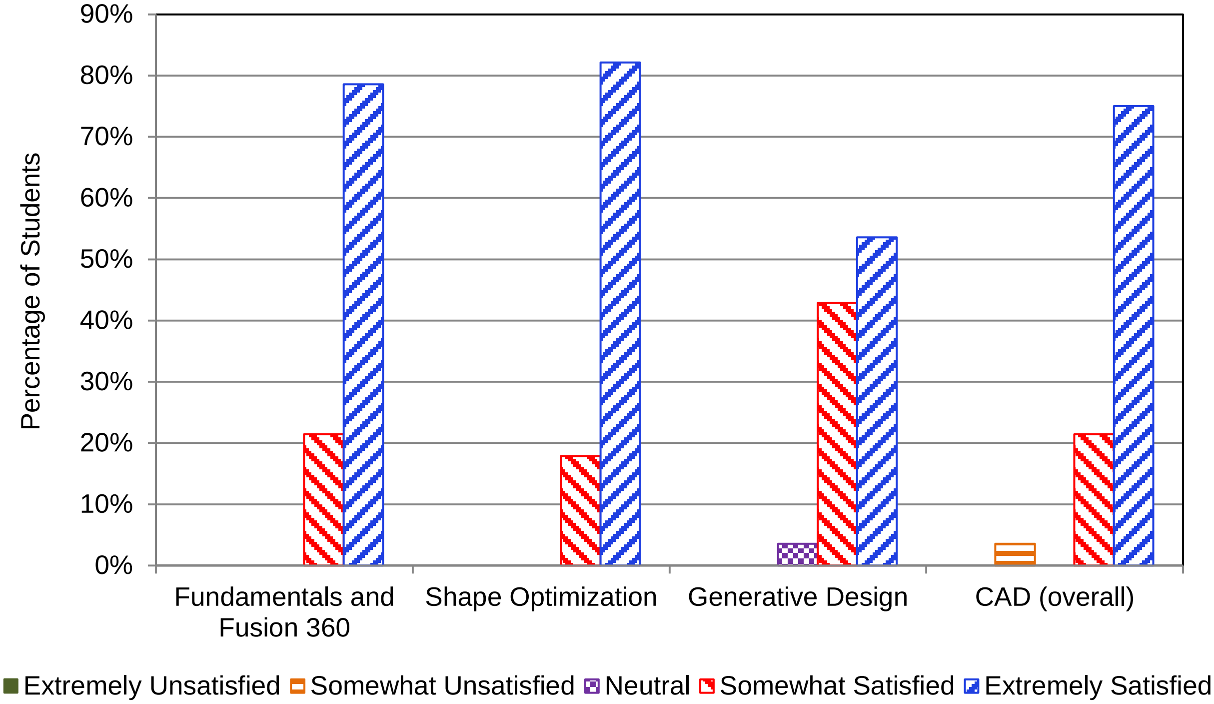

Figure 5. Survey showing satisfaction level of students in Module 1 (CAD, shape optimization and generative design). N=28 (number of participants) out of 29 students.

Module 2: Finite Element Analysis

One of the main reasons for inclusion of CAE in the curriculum is to train students with advanced engineering analysis tools for stress analysis and flow modeling. In this module, students learn fundamental concepts of FEA using hand calculations, along with novel simulation software for analyses of complex engineering structures. FEA simulations focus on basic structural analysis, buckling, modal analysis and thermal stresses. Significant emphasis is given on teaching how to choose the right type of physics for FEA simulation, understanding of element types, and applying the correct boundary conditions. After covering various types of physics, elements and pre/post-processing, students gain valuable hands-on skills to perform rigorous FEA analysis and learn how to interpret simulation results in terms of safety factors, stress, and deformation analysis. Very importantly, students also understand the importance of validating computational results against back-of-the-envelope calculations using fundamentals of statics and solid mechanics. Students also learn how to improve their design by better interpretation of results and applying design changes. In addition, students learn to generate models based on stress analysis tools to find the best designs which meet specifications and objectives (e.g. light weight, stiffness, deformation, etc.).

Figure 6 shows the survey results of questions relevant to Module 2 which covered FEA and pertinent areas. With a survey participation rate of 97%, results showed positive responses regarding the FEA activities covered in the class. 89% of the students had neutral or average satisfaction with FEA overall. Over 95% of the students were satisfied with the different components of Module 2 covering basic concepts, structural analysis, buckling and thermal stresses. Overall, the level of satisfaction for FEA was lower than CAD, which is expected given the complexity of FEA over CAD at the undergraduate level, as well as, no previous experience with FEA compared to CAD, where basics of the latter had been previously covered in the students' freshman year, as already mentioned.

Question: *How satisfied are you with Module 2 (Basic Concepts, Structural Analysis, Buckling and Modal Analysis, Thermal Stress Analysis and FEA) and activities in increasing your skills for hands-on software use and engineering design/analysis?*

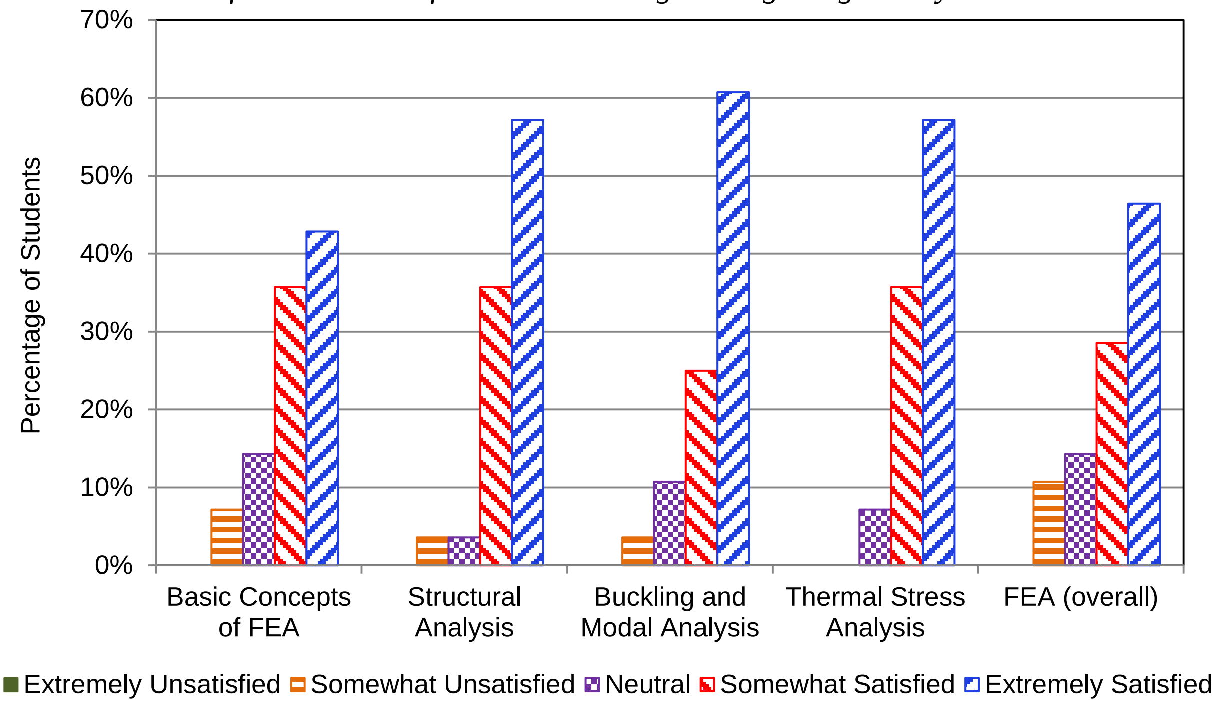

Figure 6. Survey showing satisfaction level of students in Module 2 (FEA and stress analysis). N=28 (number of participants) out of 29 students.

Module 3: Computational Fluid Dynamics

Complementary to FEA for engineering problems involving stress analysis and flow modeling, CFD is covered to train students with hands-on CFD tools for fundamental as well as complex flow problems. Internal and external flow applications such as flow in pipes and over airfoils are simulated to calculate velocity, pressure, drag coefficient and other flow parameters using commercially available CFD codes. This module first focuses on an overview of fluid dynamics, numerical analysis, and the importance of validation and verification of CFD simulation results to back-of-the-envelope calculations and/or experimental data. Then, students are given hands-on training on commercially available CFD software to analyze fluid flow problems and verify computational results. Furthermore, based on the pressure field generated by CFD, structural analysis is performed to investigate the structural integrity of mechanical systems due to the load applied from fluid flow. Such simulations allow students to work on multiphysics aspects of real-world engineering problems and to get equipped with advanced tools to tackle complex problems.

Figure 7 shows the survey results in reference to Module 3, covering CFD and pertinent topics. Results showed positive responses regarding CFD activities covered in class. 96% of the students had neutral or above average satisfaction with CFD overall, while 4% of the students were somewhat unsatisfied, but no student was extremely unsatisfied. Over 80% of the students were satisfied with the different components of Module 3 covering basic concepts of numerical analysis, fluid mechanics and examples of simulations.

<u>Question:</u> *How satisfied are you with Module 3 (Fundamentals, Fluid Dynamics Simulations and CFD) and activities in increasing your skills for hands-on software use and engineering design/analysis?*

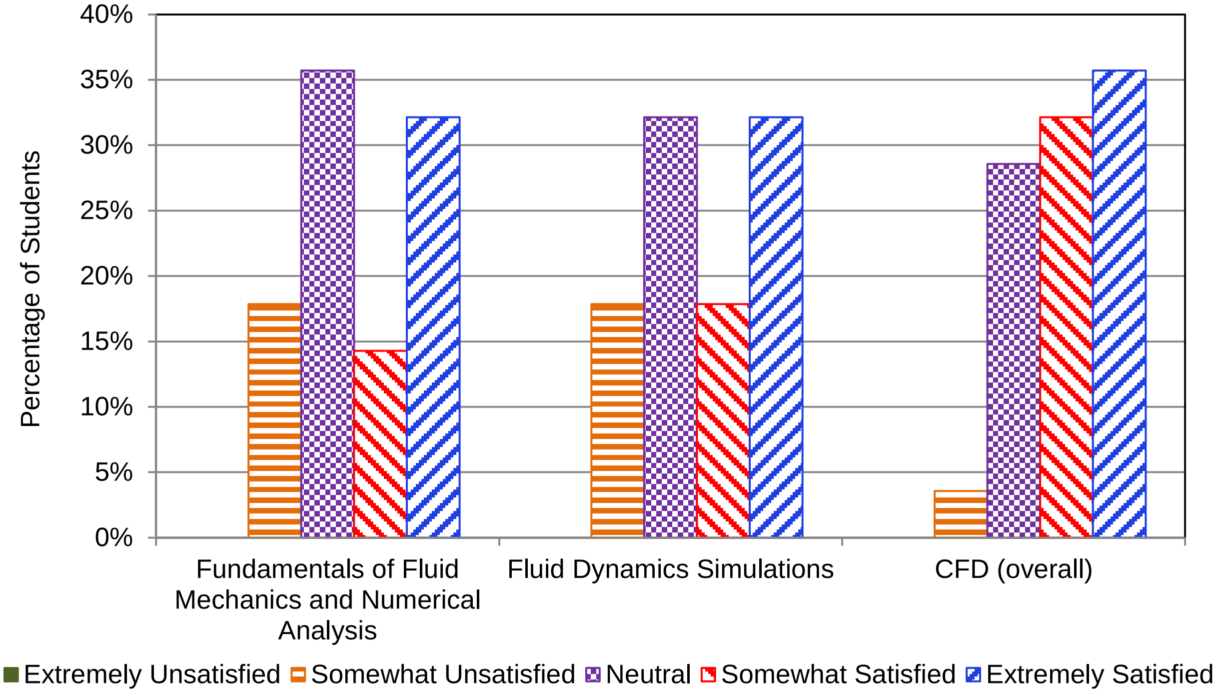

Figure 7. Survey showing satisfaction level of students in Module 3 (CFD and flow analysis). N=28 (number of participants) out of 29 students.

Overall, the level of satisfaction for CFD was lower than FEA and CAD, which is expected given the complexity of CFD over FEA and especially CAD at the undergraduate level. In addition, CFD involves an understanding of the Navier-Stokes equation, finite volume method, and numerical analysis which are more complex than finite element analysis. Overall, the module allowed students to gain hands-on skills with CFD codes toward analyzing real-world fluid flow problems.

Academic Performance and Assessment of Student Learning Outcomes

Academic performance of the students was consistent with the overall satisfaction and experience of the students, as 94% of the students received grades of C or above, while 6% of the students obtained D's, and no student failed. Students' learning outcomes were assessed by ranking how much students agreed that the CAE course increased the learning outcomes for them after taking the course.

The responses are ranked in five categories from Completely Disagree to Completely Agree. Figure 8 shows self-assessment of learning outcomes for the participants.

Rank how much you agree that the "Computer Aided Engineering" course increased the following outcomes for you:

1. Advanced CAD skills with shape optimization and generative design capabilities
2. Hands-on knowledge and understanding of structural optimization
3. Skills to design a mechanical system, apply fundamental knowledge and use Generative Design for efficient and best design solutions
4. Skills to use basics of fluid mechanics to apply to mechanical systems for rigorous and complex engineering analysis using CFD software
5. Understanding of the concepts discussed in Fluid Mechanics and Solid Mechanics courses
6. Critical thinking in design considerations
7. Overall ability for engineering design and hands-on software skills for engineering analysis and engineering practice
8. Preparedness for capstone design series
9. Readiness for the workforce and chances for better opportunities with industry-grade software skills

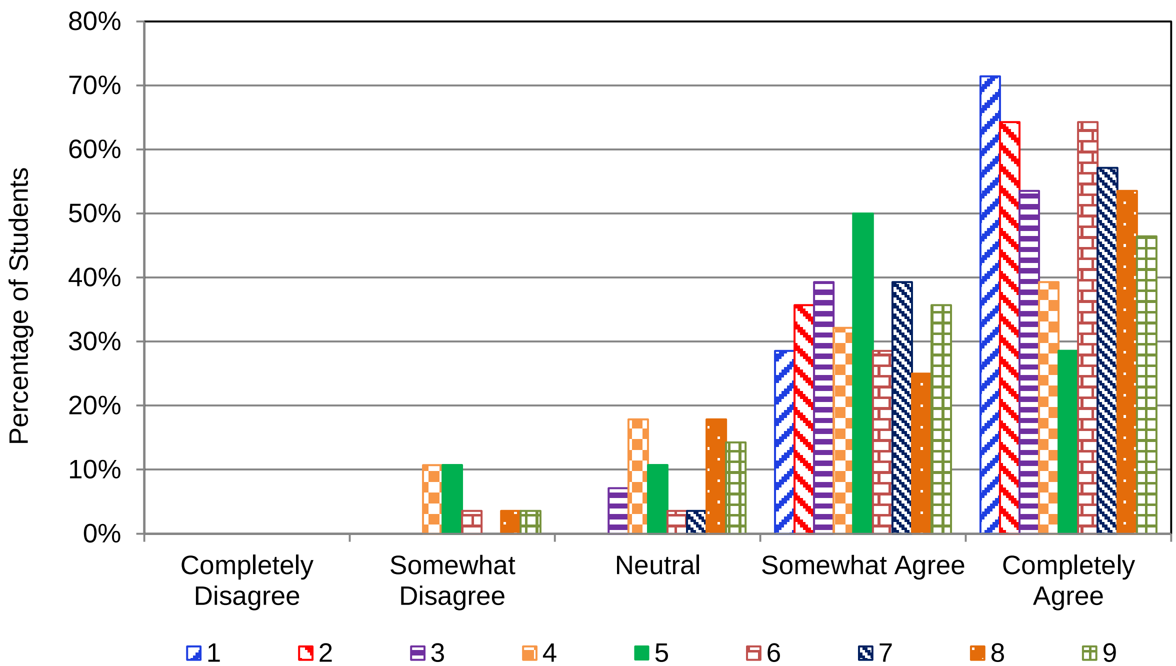

Figure 8. Student self-assessment of learning outcomes after taking the CAE course. N=28 (number of participants) out of 29 students.

As seen in the figure, a number of conclusions can be drawn based on the outcomes and the responses of the students. 88% of the students either somewhat agree or completely agree with all of the outcomes, which means that the CAE course increased their skills and hands-on knowledge with generative design, CAD, FEA and CFD. The course also helped the students gain practical engineering knowledge beyond what is taught in Fluid Mechanics and Solid

Mechanics courses. The survey indicates that the course increased students' critical thinking in design considerations and overall ability for engineering design. Very importantly, the course successfully meets objectives to better prepare students for senior design (capstone) courses as well as to increase their readiness for the workforce with rigorous tools. These results also reveal that all of the students had neutral or above average assessment with regard to outcomes 1, 2, 3 and 7, which can be mapped to skills associated with CAD, shape optimization and generative design capabilities. The somewhat lower ratings on topics which students had no previous knowledge or experience with, including FEA or CFD, are expected, as students may have had some reservations with assessing those outcomes. As a continuous improvement strategy to increase the overall satisfaction of the students in FEA and CFD, these modules would need additional sessions for theoretical background and hands-on exercises.

In terms of overall proficiency on software packages and hands-on skills, students were asked to rate their proficiency in engineering analysis and design software as a result of taking the CAE course. Figure 9 shows results of this question.

Rate your proficiency in engineering analysis and design software as a result of taking the "Computer Aided Engineering" course

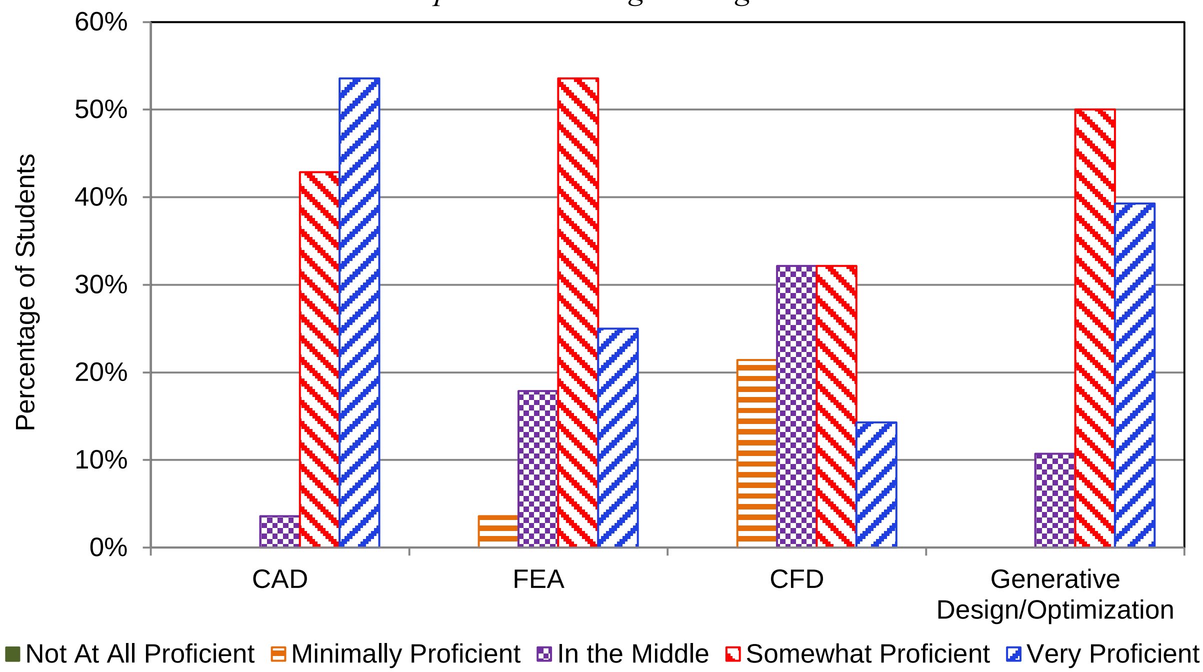

Figure 9. Student self-assessment of overall proficiency in engineering analysis and design software as a result of taking the CAE course. N=28 (number of participants) out of 29 students.

Overall, 94% of the students indicated average to high proficiency on generative design, optimization, CAD, FEA and CFD. All of the students responded average to high proficiency on CAD and generative design/optimization. Average to high proficiency on FEA and CFD was 96% and 79%, respectively. These findings are consistent with the previous assessment of student learning outcomes that students had no previous knowledge or experience with FEA and CFD. Moreover, CFD is more complex than FEA from the perspective of complicated PDEs associated with the Navier-Stokes equation, discretization, meshing and computationally expensive process. Thus, it is expected that students would have greater confidence in CAD than

FEA and in FEA than CFD. However, for those students who are interested in building additional expertise and skills in one or more of these areas, the curriculum offers specializations and technical electives (e.g. CAD/CAM, Computational Fluid Dynamics) which are typically taken at the senior year.

Conclusions

Computer Aided Engineering, which integrates advanced CAD, FEA, CFD and optimization, is a core engineering course which is developed and included in an undergraduate curriculum to teach junior-level students advanced engineering tools to design complex mechanical engineering systems, perform analysis using commercially available FEA and CFD software, and optimize the final design using a revolutionary design method called Generative Design using Autodesk Fusion 360. Surveying of students shows that the course increased their hands-on knowledge and skills with respect to design and engineering analysis software, along with validation and verification against back-of-the-envelope calculations and/or experimental data. It was also evident that the students gained additional critical thinking skills in design considerations. The most challenging part of the course was to cover four major modules in a 3-credit course while the students had no previous knowledge of FEA and CFD. Thus, it was observed that FEA and CFD modules were less satisfactory to the students due to the perceived level of difficultly of those modules, which indicates a potential need to incorporate additional lectures and hands-on exercises as a continuous improvement strategy in the future. Additionally, it is suggested that more project-based assignments would be needed to integrate the four modules to enhance the student learning experience. Overall, the objectives of the course were well met based on the self-assessment survey administered to students, indicating that the course increased the students' preparedness for the capstone design series courses, as well as, their readiness for entering the workforce with greater confidence.

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