Breaking Boundaries: Introducing First-Year Engineering Students to Computational Fluid Dynamics

Juan D. Ortega-Alvarez
Department of Engineering Eduction
Virginia Tech
Blacksburg, VA, USA
jdortegaa@vt.edu

Matthew Norris
Department of Engineering Eduction
Virginia Tech
Blacksburg, VA, USA
mbnorris@vt.edu

Michelle Soledad
Department of Engineering Eduction
Virginia Tech
Blacksburg, VA, USA
msoled21@vt.edu

***Abstract*—This innovative practice full paper discusses the implementations of computational fluid dynamics (CFD) in a first-year engineering course, focusing on its aims and outcomes. First-year engineering courses typically introduce students to skills transversal to engineering disciplines like programming and computer-aided design. These courses often incorporate semester-long, team-based projects aimed at contextualizing these skills and fostering the development of professional skills like teamwork and communication. Additionally, students are frequently tasked with applying design skills including scoping, prototyping, testing, and decision-making.**

The COVID-19 pandemic prompted most first-year engineering programs in the US to offer their courses online, posing significant challenges for courses with substantial hands-on tasks such as physical prototyping and testing. Although most programs have since returned to in-person instruction, certain online strategies and tools have proven valuable in traditional settings as well. Examples include asynchronous video resources and automatic feedback questionnaires for independent student exploration, accessible Zoom office hours, and simulation software to supplement in-person building and testing.

One powerful simulation tool in engineering is computational fluid dynamics (CFD). Integrating CFD into a first-year engineering curriculum can yield both positive and negative outcomes. On the positive side, CFD provides a simulated experimentation platform, enabling students to explore the outcomes of testing multiple designs and thus make informed decisions. However, it can also lead to surface-level understanding, overreliance on tools, and potential misconceptions and misinterpretations.

This paper outlines the implementation of CFD in a project-based first-year engineering course conducted in person. CFD simulation was initially introduced in Spring 2021 as a response to the pandemic restrictions and has since been adapted for continued use in face-to-face instruction. This study aims to explore students' perceptions of the benefits and challenges associated with their interaction with CFD. Results from surveying four sections of the course in Spring 2024 indicate that most students had a positive experience with the tool. However, several students perceive a lack of disciplinary knowledge as a barrier to fully understand the use of CFD. These preliminary findings make a compelling case for maintaining CFD at the first-year level and suggest adjustments to enhance its effectiveness.

Keywords—General Engineering; First-year Engineering; Computational Fluid Dynamics; Learning with Models

I. Introduction

Introductory engineering courses and first-year engineering programs are common across colleges and universities in the United States. Their primary goals typically involve introducing students to various engineering disciplines while emphasizing core skills such as communication, teamwork, problem-solving, and design [1]. The learning outcomes of these programs often involve basic proficiency with software tools like programming and computer-aided design (CAD). Additionally, students must learn to make data-informed decisions, often within the context of design projects that involve prototyping and testing. The use of simulated or synthetic data is common in educational settings, facilitated by software applications that provide learner-friendly interfaces. These interfaces represent real phenomena in a simplified manner, yet are powered by complex mathematical models [2], [3]. The aim of such applications is to help students grasp core scientific concepts without necessarily focusing on the underlying modeling equations. However, it is less common for first-year engineering students to engage in creating their own simulated testing platforms using more general purpose tools like computational fluid dynamics (CFD).

This paper focuses on the implementation of CFD as an alternative to physical testing in a first-year engineering project-based course at Virginia Tech. Instructors initially pursued this implementation due to the restrictions imposed by the COVID-19 pandemic, which limited access to physical classrooms, makerspaces, and testing equipment. However, several instructors opted to retain CFD-related activities and assignments after returning to in-person classes due to the perceived benefits it offers. These benefits include the ability to run tests with computer-generated models of full-sized, large-scale designs at varying conditions as well as the opportunity to critically evaluate simulated testing results and compare them to physical results [4]. Furthermore, since CAD modeling has been integral to the course, testing the CAD models seems like a reasonable next step. On the other hand, introducing sophisticated tools like CFD into foundational engineering courses may lead to student cognitive overload and shift the focus from the fundamental steps of engineering design to the operational details of a specific tool [5].

This paper discusses the integration of CFD in a first-year engineering course, focusing on strategies employed to maximize the anticipated benefits and mitigate the potential risks. Students' perceptions of their understanding and the usefulness of CFD, along with their answers to conceptual questions, serve as indicators to evaluate the effectiveness of this integration and inform decisions regarding its retention, modification, or removal from the course.

II. Context

A. Innovative Teacing Practice

The innovative practice described in this paper has been incorporated into an introductory engineering course designated as ENGE 1216. This course constitutes the second part of the first-year engineering (FYE) two-course sequence at Virginia Tech. The curriculum of ENGE 1216 revolves around a semester-long project that provides students with a meaningful context to develop teamwork, communication, problem-solving, and engineering design skills. The project entails tasks such as creating sketches and drawings, constructing multiple physical prototypes with increasing fidelity, and conducting physical testing to suggest and implement changes to improve the design concept. Instructors have flexibility to offer various project topics, which include designing an aesthetically-pleasing vertical-axis wind turbine (VAWT), a musical instrument, or an artifact aimed at solving a problem identified by the students. Typically, instructors select only one of these project alternatives for all their sections. This paper focuses on the experience of multiple instructors and students working with the VAWT project.

During the COVID-19 pandemic, the instruction of FYE courses at Virginia Tech transitioned to an online format. Recognizing the challenges this posed for hands-on building and testing, the makerspace serving FYE students stepped in to facilitate prototype construction by creating and shipping prototyping kits. These kits included wooden dowel rods, foam core, cardboard, and various attachment materials (e.g., tape, twine, nylon). Students were encouraged to build and test their prototypes with a box fan or by subjecting them to prevailing wind conditions outdoors. However, this basic testing method lacked the detailed insights that students could obtain on campus by testing their final prototypes in a controlled environment. On campus, testing was carried out in a testing device equipped with a three-speed fan, an anemometer to measure wind speed, a small generator, and a meter to record voltage and resistance readings. To provide students in the online format with an opportunity for a structured testing experience that could offer insights similar to the in-person environment, the instructional team decided to introduce simulated testing via computational fluid dynamics (CFD) [6].

Students in all sections of ENGE 1216 use the CAD software SolidWorks to create 3D models for their project. Before the pandemic, in the context of a different project, makerspace personnel implemented the use of CFD to enhance testing of small flying vehicles by utilizing the flow simulation capabilities of SolidWorks. When the pandemic necessitated a shift to remote instruction, instructors leveraged the expertise of makerspace assistants to design a CFD testing activity for the VAWT project in online format. For simplicity, instead of a dynamic rotating simulation, the activity instructed students to conduct multiple static simulations, manually rotate the turbine model, and then average the results. This approach also has the advantage of providing a data set for students to process and analyze in MATLAB. Full implementation of this activity entailed the complementary pieces shown in Fig. 1.

Collectively, these different pieces serve three main purposes: 1) to provide students with enough information to understand the tool and use it autonomously; 2) to provide opportunities for students and instructors to assess such practical understanding; and 3) to seamlessly integrate the use of CFD into the design project as an example of the usefulness of simulations and simulated testing in the engineering design process. While the majority of these pieces are preparatory and focus on individual student learning and skill building, the project deliverables themselves are team-based. Moreover, subteams within each larger team bore the responsibility of implementing the CFD simulation for their VAWT design. All of these pieces were retained and refined when the course transitioned back to an in-person format. The only major change was the addition to the project final report guidelines of a request for teams to critically compare the results obtained from the simulated CFD testing with the data gathered from physical testing of their VAWT prototypes.

The past two years of offering ENGE 1216 with the VAWT project, as reflected by instructor experiences and student comments, suggest that integrating Computational Fluid Dynamics (CFD) has several benefits. In particular, students have highlighted how CFD can increase their interest and engagement in the project, and connect them to more technical aspects of engineering, which some have reported missing from these introductory courses. However, it was unclear whether all students in the class or only those in the CFD subteams are reaping these benefits.

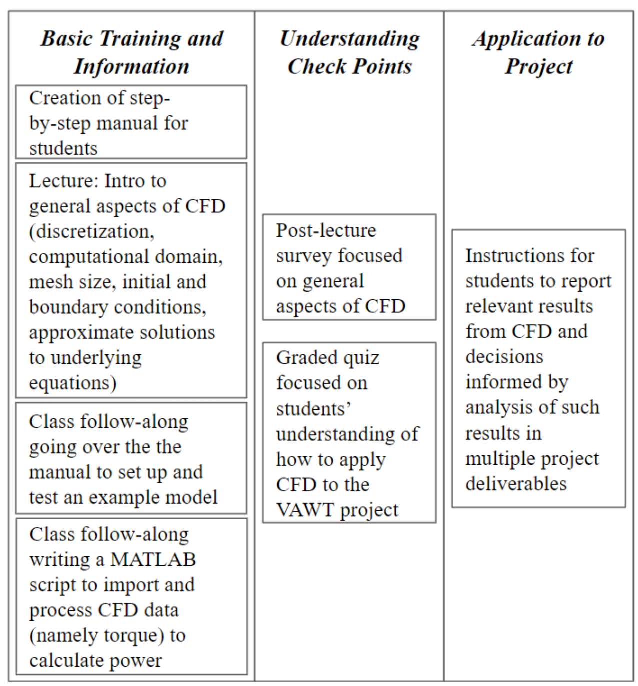

Fig. 1. Complementary components of the CFD integration.

B. Relevant Literature

Modeling and simulations are effective tools for instruction in science education across a wide range of fields including physics [7], mathematics [8], and engineering [2], [9], [10]. A significant advantage of simulation in the case of engineering is the higher speed, lower cost, and greater accessibility when compared to physical prototyping [5]. Advances in hardware and software continue to make more advanced physics simulations possible with commonly available computing resources. The rapid advancement of high-performance computing in the 1990s, widespread adoption of parallel processing in the 2000s, and the shift toward GPUs from CPUs in the 2010s has made high-fidelity computation more accessible [11].

Existing literature in engineering education frames the use of software and simulation tools in one of two ways: 1) as the focus of the learning, or 2) as a method of teaching a particular concept. The first of these approaches is extremely common and in some ways serves as a precursor for the second approach. The introduction of software packages and coding languages as 'bootcamps' or certification courses teaches students how to use tools like MathWorks Simulink, Ansys, or SolidWorks FEM. In these instances, mastery of the software language or modeling package is the learning objective. These and other software packages can model a wide range of physical processes including the use of electromechanical systems [12] and dynamic electrical power generation [13]. Current literature focuses primarily on the use of software and simulation tools as a method for improving student learning of specific disciplinary concepts. These software tools are often used to provide more authentic or dynamic examples of engineering systems for students to engage with to improve their understanding. An example of this is the use of finite element analysis software packages (e.g., Ansys, Abaqus, OpenFOAM) being used to model structural loads and provide more illustrative instructions on stress and strain for various applications [14]. These two approaches are both called modeling and use the same software packages, but the focus and purpose of student learning is different. For the purposes of this paper, these two framings found in literature will be referred to as *Teaching to Model* and *Teaching with Models* respectively.

Instructors have begun to use both aforementioned framings in applicable engineering courses prior to the pandemic. However, their importance and usefulness as modes of learning became more prominent as institutions sought to pivot active learning and project-based strategies to online mode in the absence of in-person instruction. Instructors at the University of Hartford, for example, have been using finite element analysis (FEA) and computational fluid dynamics (CFD) as learning tools to introduce fundamental concepts and promote conceptual understanding since before the pandemic. An analysis of student performance, deliverables, and feedback of students in the Mechanical, Aerospace and Acoustical Engineering from 2015 to 2022, covering pre-, during, and post-pandemic learning environments, indicates positive student experiences and improved student success across all learning environments. The primary adjustment made during the pandemic was to reduce student workload. Gains derived from the use of simulations as a learning tool remained positive despite this adjustment [15]. Fluid Mechanics instruction at the Pontificia Universidad Católica del Perú, on the other hand, began adopting blending learning strategies that included virtual computational fluid dynamics simulations in 2015. A design-based research study released post-pandemic highlighted the advantages that simulations were able to provide to pandemic-era learning environments in South America [16]. The authors recommended the continued use of computational fluid dynamics and visualizations in laboratory instruction moving forward, citing, among other advantages, enhanced opportunity for experimental skills development among engineering students in developing countries.

While simulations are an effective tool for teaching a wide variety of disciplinary concepts, their implementation as a learning intervention is not without challenges. A minimum level of understanding and experience is required for students to correctly interpret results. Students must first learn to model in order to use a simulation tool to learn with models. Students can become over-focused on getting their software to run correctly at the cost of decreased understanding of the concepts or physical phenomena underlying their models [5]. Students can become fixated on debugging their simulation or cognitively overloaded, which is detrimental to their learning [17], [18], [19].

The VAWT project described in this paper provides an illustrative context highlighting the different ways in which modeling tools can be used with respect to student learning. In the context of the VAWT project, *Teaching To Model* occurs when introducing students to the CFD simulation tools within SolidWorks, and subsequent instructions on how to establish a computational domain and initial conditions. *Teaching with Models for a Disciplinary Concept* occurs when CFD is used to visualize pressure and wind speed variations across CAD models to help students understand aerodynamic drag and estimate power outputs. *Teaching with Models for an Interdisciplinary Concept* occurs when students are instructed on how to use CFD results to iteratively change their product to meet overall design requirements. Clearly, these different framings are not mutually exclusive within the context of a single project. It is necessary that students are taught to model to the point that their software skills do not inhibit their progress, but the same simulation tool can then be used to teach disciplinary concepts like air drag and rotor efficiency.

III. Methods

The CFD activity has been consistently implemented by some instructors in multiple sections of ENGE 1216 since the return to in-person instruction in Fall 2021. Anecdotal evidence and reflections span this period of over three years. Some instructors have kept the activity as described on this paper, while others have made it optional for student teams. However, assessment data presented on this paper was collected during Spring 2024 from four sections of the course, with two instructors teaching two sections each. Each section had ~70 students for a total of 284 students. Both instructors followed the implementation procedure described in Fig. 1.

Towards the end of the term (week 13), the instructors administered a survey as a for-credit class assignment graded on the basis of completion. The survey was designed to explore three aspects of the students' experience: 1) perceptions of understanding and usefulness of CFD; 2) understanding of general aspects of CFD; and 3) understanding of advantages and limitations of using CFD in engineering design. In addition, the survey asked students to report whether they were part of the CFD subteam and rate their level of involvement with CFD-related parts of the project. Involvement (one item) and perceptions (four items) questions were presented on a five-point Likert scale, whereas conceptual understanding checks were presented as True/False statements (four for general aspects and ten for application to design). The survey also included an open-ended question asking students if they found CFD to be useful/not useful and why. The involvement and the four perceptions questions were as follows:

1) *Rate your involvement with the CFD simulation, regardless of whether you were in the CFD subteam.*
2) *How confident are you in your understanding of the purpose and limitations of CFD in the context of the Vertical Axis Wind Turbine (VAWT) project?*
3) *Do you feel a limited technical knowledge (e.g., aerodynamics, electric power generation, etc.) gets in the way of your understanding of the CFD results and what they mean for your VAWT project? (note that lower ratings are better for this question)*
4) *How proficient do you feel with CFD in the context of the VAWT project?*
5) *How useful do you find CFD for the engineering design process?*

The True/False statements aimed at probing students' basic conceptual understanding focusing on key CFD concepts highlighted during class. These statement are listed below:

General concepts of CFD

- CFD provides a high-fidelity model of airflow velocity and pressure over the simulated domain.
- In CFD, the discretization of the domain provides an exact solution to the mathematical equations underlying the model.
- A finer simulation mesh produces more accurate results, but at the cost of more computational resources required to obtain a solution.
- Solutions generated by CFD are not sensitive to changes in initial and boundary conditions.

Understanding of CFD applied to real engineering design

- Solutions generated by CFD always account for variable environmental conditions in the real world.
- CFD is generally less expensive to conduct than field experiments using physical models.
- If there is a difference between your results from your physical prototype and your CFD model (at the same scale), then the CFD results are more accurate.
- Making changes to computer models and running simulations is typically faster than changing and retesting physical models.
- A CFD simulation can provide
  - An estimate of your design's performance
  - The exact real-life performance of your full-scale design
  - Design requirements for your project
  - Trustworthy results that do not require subject-matter knowledge to interpret
  - Indications of critical points in your design that require attention
  - Feedback to inform the direction of following design iterations

IV. Results

A. *Involvment & Perceptions*

A total of 224 students completed the survey across all four sections. Fig. 2 illustrates the distribution of students' responses to the five Likert-scale items on a five-point scale, with 1 being the lower end (e.g., not involved at all, not proficient at all) and 5 the upper end of the scale (e.g., very involved, very proficient). Note that the knowledge barrier item is an exception, as 1 indicates no perception of knowledge limitation while 5 indicates a perceived severe knowledge limitation to understand and work with CFD. Interestingly, the distribution of students' responses for this item is nearly symmetrical.

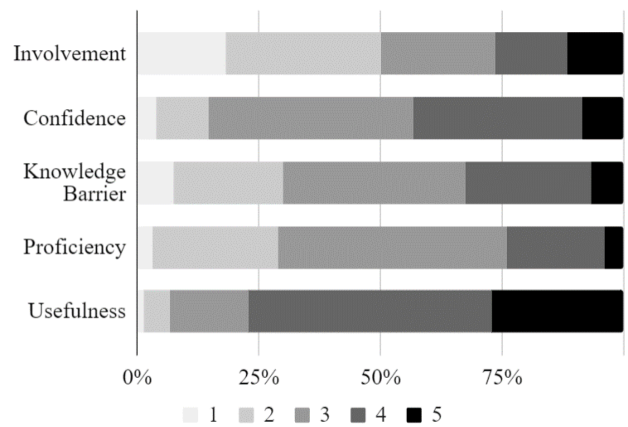

Fig. 2. Percentual distribution of students' responses to Likert-scale items.

Out of the 224 students, 63 (28%) reported that they were members of the CFD subteam. Student membership across project subteams was not exclusive, as students were able to work on more than one, but the number of subteams a student worked on (M = 1.36, SD = 0.52) was generally low. Correlations were estimated by computing Kendall's τ_b for each question, as shown in Table I.

Students' perception of their own proficiency with CFD beyond the context of the VAWT project was significantly correlated with their involvement in the CFD simulation for the project, $\tau_b = .37$, $p < .001$, and their confidence with CFD within the project, $\tau_b = .43$, $p < .001$; involvement with the simulation was also correlated with confidence with CFD within the project, $\tau_b = .27$, $p < .001$. There was also a significant relationship between how useful students found CFD to be for the engineering design process and their confidence with CFD within the project, $\tau_b = .16$, $p < .01$, as well as their perception of their own proficiency with CFD beyond the context of the VAWT project, $\tau_b = .21$, $p < .001$.

TABLE I. DESCRIPTIVE STATISTICS AND CORRELATIONS

Variable	Likert score means, standard deviations, and correlations with confidence intervals[a]					
	M	*SD*	*Inv.*	*Conf.*	*Tech. Know.*	*Prof.*
Involvement	2.70	1.26				
Confidence	3.33	0.92	.27*** [.19, .35]			
Knowledge Barrier	3.02	1.03	-.02 [-.11, .07]	-.12 [-.21, -.03]		
Proficiency	2.96	0.86	.37*** [.30, .44]	.43*** [.35, .50]	-.13 [-.21, -.04]	
Usefulness	3.96	0.88	.05 [-.02, .13]	.16** [.08, .24]	-.02 [-.11, .06]	.21*** [.13, .29]

[a] M and SD are mean and standard deviation, respectively. N = 224. Values in square brackets indicate 95% confidence intervals for each correlation. ** $p < .01$, *** $p < .001$.

B. Perceptions vs. Subteam Membership and Performance

CFD subteam members' self-reported involvement with the simulation (Mdn = 4) differed significantly from students on other subteams, namely CAD, programming, and prototyping (Mdn = 2), W = 829.5, p < .001, r = .70. Although small, there were also significant differences in students' perceptions of confidence (W = 3,796.5, p < .01, r = .21) and proficiency (W = 3,231.0, p < .001, r = .30) between students in the CFD subteam and students in other subteams. These results are not surprising since students on the CFD subteam were primarily responsible for creating and running the simulation. There were no significant differences due to membership between students in other subteams (see Table II).

TABLE II. WILCOXON RANK-SUM TEST FOR SUBTEAM MEMBERSHIP

Perception[b]	Subteam Membership		W	*r*
	CFD *Mdn*	Other *Mdn*		
Involvement	4	2	829.5***	.669
Confidence	4	3	3,796.5**	.258
Proficiency	3	3	3,231.0***	.302
Knowledge Barrier	3	3	5,148.5	.012
Usefulness	4	4	4,630.0	.073

[b] Bonferroni correction applied to *p* values, N = 224, * $p < .05$, ** $p < .01$, *** $p < .001$

Students generally answered most of the 14 True/False questions correctly (*Mdn* = 12, SD = 1.91) regardless of their subteam membership. Only two questions showed a correct response rate below 70%, with 153 students (68.30%) correctly marking as false the statement '*In CFD, the discretization of the domain provides an exact solution to the mathematical equations underlying the model*', and only 85 (37.95%) correctly marking as false the statement '*A CFD simulation can provide... [design requirements for your project]*'. However, there was no correlation between answers to these two questions and students' subteam membership. Similarly, there was no significant correlation between students' perceptions of their involvement, confidence, or proficiency and the number of True/False questions they answered correctly.

C. Perceptions on usefulness of CFD

Thematic analysis was employed to qualitatively analyze the responses to the open-ended question '*How useful do you find CFD for the engineering design process?*' with the aim of allowing students' perceptions of CFD as a learning tool to emerge and understanding students' experiences in a more nuanced manner [20]. One of the researchers used first-cycle coding to generate 23 initial codes which were further categorized into six themes. The analysis allowed all student perceptions to emerge, which resulted in some responses having more than one label during initial coding, representing multiple views expressed in the same response. The most salient theme was the notion of CFD as being useful to *simulate real-world conditions*, representing the perceptions of 66.82% of the respondents.

Most respondents (217/224) indicated that they found the use of computational fluid dynamics simulations useful for their VAWT project. Fig. 3 illustrates the various reasons behind students' positive perceptions of the usefulness of CFD.

Of the respondents that expressed perceptions that CFD was useful to their project, 149 shared the general perspective that CFD was useful because it *provided the ability to simulate design performance in a variety of real-world conditions*. These responses were further categorized into the ability to *visualize design performance* in general (76/224); *visualize design performance relative to external factors* (62/224); and *visualize design limitations* (11/224). Another salient perception is that CFD facilitates *visualization of design for design iteration and improvement* (37/224), with respondents sharing that they were able to undergo several design iterations and improve their designs with the ability to run CFD.

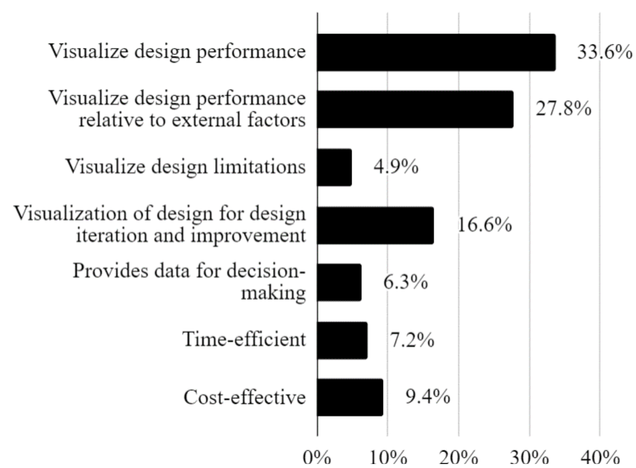

Fig. 3. Student perceptions of the usefulness of CFD.

Some respondents (6/224) did not feel that CFD had a positive impact on their learning. Although these statements were not ubiquitous in the data, one respondent expressed inability to recognize how CFD was useful for the specific engineering discipline that they were interested in. There were also a number of respondents (22/224) who, although they recognized and acknowledged the usefulness of CFD, shared challenges that diminished their learning experience and ability to appreciate the inclusion of CFD in the course, such as a general lack of understanding of how to interpret the data, or lack of involvement in the process since they were not part of the CFD sub-team.

V. Discussion

For the analysis and discussion of mean scores, the following interpretation scale has been used (reversed for knowledge barrier): 1-2 Not good; 2-3 Moderately good; 3-4 Good; 4-5 Very good. For instance, the mean score for involvement (M=2.70) is just moderately good, but in fact encouraging considering that only 28% of the students were part of the CFD subteam. In contrast, the mean score for perceived usefulness (M=3.96) is borderline very good and the positively skewed distribution for this item observable in Fig 2 confirms it. This suggests that, while there is plenty of room for improvement, efforts to integrate CFD into the class project are helping students across different subteams recognize how their work impacts or is impacted by simulation outcomes.

Nevertheless, the level of involvement with CFD applied to the project seems to have a significant impact on the experience. Students' perception of involvement correlates significantly with self-reported perceptions of confidence and proficiency. In other words, students who went beyond the individual preparatory activities and did CFD-related work for the project reported higher levels of confidence in their understanding of CFD general concepts and proficiency to apply it to their VAWT project. However, the mean score for confidence (M=3.33) suggests that students with less involvement also perceived themselves as moderately able to discuss CFD conceptually and explain how to apply it to the project. The implementation manual, CFD lecture, and follow-along demos during class seem to have done a good job in fostering students' confidence in their understanding of the broad aspects and limitations of applying CFD to the VAWT project.

In contrast, students' perception of proficiency was probably impacted by participation in the hands-on task of running CFD simulations for the project, which was mostly carried out by the CFD subteams. Therefore, the lower mean score found for proficiency (M=2.96) is reasonable yet borderline good. Note that while students who were members of the CFD subteam reported significantly higher involvement, students in other subteams were not precluded from the opportunity to engage in CFD-related work. Moreover, they were required to discuss explicit connections between their own work and input for or insights derived from the simulations. A perceived knowledge barrier (M=3.02) seems to be one of the factors negatively affecting students' perceptions of both their proficiency and confidence. This supports the idea of a threshold of disciplinary knowledge necessary for Teaching with models for a disciplinary concept to be effective.

Despite the moderate results found for confidence and proficiency, the mean score for perceptions of the usefulness of CDF, as mentioned before, was notably higher and borderline very good (M=3.96). This is an encouraging result since the main purpose of this innovative practice is to expose students to a sophisticated tool that can be used in engineering design and not to develop high proficiency in its use. With sufficient training on Teaching to Model using SolidWorks fluid simulation capabilities, this innovative practice focused on Teaching with Models introducing both disciplinary aspects of wind turbines and, more importantly, the relevance of simulated testing as an interdisciplinary tool in engineering design.

The comparison between students' self-reported confidence in their understanding of basic CFD concepts and proficiency to implement CFD in the context of the VAWT project was inconclusive. Overall, students performed better on the True/False questions than they rated their confidence and proficiency. Arguably, this discrepancy stems from limitations of the ad hoc questionnaire used to assess students' conceptual understanding of CFD.

Finally, qualitative analysis of students' perceptions of the usefulness of CFD revealed that, in general, respondents shared positive learning experiences that aligned with advantages associated with CFD as shared in literature (e.g., [15], [16]). One student shared:

> *"CFD provides feedback and data that would otherwise be impossible for us to gather in this classroom setting. Even for engineers with access to industrial wind tunnels, CFD is still useful in prototyping and development since they can conduct more tests, for cheaper, and without a physical prototype."*

This and other similar perspectives indicate that it is useful to continue CFD simulations for the specific context of classes that are engaged in the Vertical Axis Wind Turbine project, as it has advantages and learning applications that go beyond the need for virtual testing as a consequence of fully online instruction triggered by an emergency situation.

Although there are fewer perspectives that indicate challenges and lack of appreciation for the usefulness of CFD, it is important for instructors to consider in-class messaging and how to design and structure learning activities to ensure that these concerns are addressed. For example, a student commented:

> *"I do think it is useful and important to both our design testing and education. I think CFD and simulations are extremely important in the real world for engineering and as a knowledge and it is very useful in this context. But I think that it doesn't fit the scale of this project well. If we had started this process 1-2 weeks earlier and had more time to learn and understand what CFD is and how to implement it's results into our design it would be useful, but right now it just feels like something we have to check off the list of things we did."*

It is encouraging to see that the student has an appreciation for virtual simulations as a learning tool, but this comment indicates a need to revisit how CFD is presented and integrated into the curriculum to ensure that its associated gains are maximized while considering the inherent limitations of a 2-credit first year engineering course.

VI. Conclusion

This paper discussed the implementation of CFD into a first-year engineering class as a means to conduct simulated testing for a vertical-axis wind turbine design project. Anecdotal information—including feedback from students—collected by instructors using this approach, highlights multiple benefits of this implementation, including testing of large designs, increased technical appeal, and increased engagement with the project. However, instructors who designed and implemented this innovative practice were aware of potential disadvantages, such as cognitive overload and shift of focus from relevant learning outcomes to the specifics of a rather sophisticated tool. Therefore, the design drew upon an intentionally scaffolded approach, with students receiving ample yet simple information and instructions and multiple understanding checks. This approach is consistent with the idea of Teaching with Models whereby the model becomes a tool for learning and not the ultimate outcome of the learning experience. Moreover, given the emphasis on the steps of engineering design as the actual outcome of the course, this innovative practice fits the description of Teaching with Models for interdisciplinary Concepts.

To verify and complement the anecdotal information, a survey was administered to students in four sections of the course during the Fall 2024 semester. Results from the survey suggest that the implementation has been effective in helping students understand the usefulness of simulated testing through CFD in engineering design. Benefits related to proficiency in applying CFD may be more pronounced among students who worked on creating and running simulations to test their designs. Altogether, these results and experiences indicate that keeping the CFD component as an integral part of the VAWT project supports the achievement of a major learning outcome of the course. Future offerings should include activities aimed at lowering the perception of technical and disciplinary knowledge as a barrier to fully grasp CFD within the context of the project. From an assessment perspective, a more robust instrument to measure students' conceptual understanding of CFD related concepts will be required.

REFERENCES

[1] F. Aloul, I. Zualkernan, G. Husseini, A. El-Hag, and Y. Al-Assaf, "A case study of a college-wide first-year undergraduate engineering course," Eur. J. Eng. Educ., vol. 40, no. 1, pp. 32–51, Jan. 2015, doi: 10.1080/03043797.2014.903229.

[2] A. J. Magana and T. de Jong, "Modeling and simulation practices in engineering education," Comput. Appl. Eng. Educ., vol. 26, no. 4, pp. 731–738, 2018, doi: 10.1002/cae.21980.

[3] H. A. Diefes-dux and P. K. Imbrie, "Modeling Activities in a First-YEAR Engineering Course," in Models and Modeling in Engineering Education, Brill, 2008, pp. 55–92. doi: 10.1163/9789087904043_005.

[4] J. D. Ortega-Alvarez, M. James, C. Twyman, B. Chambers, and T. Chowdhury, "Lessons Learned Adapting a First-Year-Engineering Project-Based Course to an Online Format," presented at the 2022 ASEE Annual Conference & Exposition, Aug. 2022. Accessed: May 10, 2024. [Online]. Available: https://peer.asee.org/lessons-learned-adapting-a-first-year-engineering-project-based-course-to-an-online-format

[5] R. Martínez-Cuenca, R. Mondragón, L. Hernández, S. Torró, J. E. Juliá, and S. Chiva, "Learning basic engineering concepts through the use of computational fluid dynamics," INTED2014 Proc., pp. 4212–4217, 2014.

[6] B. Chan, T. B. Asad, and D. Bairaktarova, "Simulating an engineering workplace: a new approach to prototype-based team project," in Towards a new future in engineering education, new scenarios that european alliances of tech universities open up, Universitat Politècnica de Catalunya, 2022, pp. 1058–1066. Accessed: Aug. 12, 2024. [Online]. Available: https://upcommons.upc.edu/handle/2117/384450

[7] N. Shin, D. H. Jonassen, and S. McGee, "Predictors of well‐structured and ill‐structured problem solving in an astronomy simulation," J. Res. Sci. Teach., vol. 40, no. 1, pp. 6‐33, Jan. 2003, doi: 10.1002/tea.10058.

[8] K. H. Cheong, J. M. Koh, D. J. Yeo, Z. X. Tan, B. O. E. Boo, and G. Y. Lee, "Paradoxical simulations to enhance education in mathematics," IEEE Access, vol. 7, pp. 17941–17950, 2019.

[9] L. Davidovitch, A. Parush, and A. Shtub, "Simulation‐based Learning in Engineering Education: Performance and Transfer in Learning Project Management," J. Eng. Educ., vol. 95, no. 4, pp. 289‐299, Oct. 2006, doi: 10.1002/j.2168-9830.2006.tb00904.x.

[10] S. Guikema, L. Ortolano, S. B. Ohshita, and P. Collins, "Using Simulation to Teach Negotiation Processes to Environmental Engineers," J. Eng. Educ., vol. 90, no. 4, pp. 631–635, Oct. 2001, doi: 10.1002/j.2168-9830.2001.tb00651.x.

[11] B. van Leer and K. G. Powell, "Introduction to computational fluid dynamics," Encycl. Aerosp. Eng., 2010, Accessed: May 13, 2024. [Online]. Available: https://www.researchgate.net/profile/Bram-Van-Leer/publication/229495182_Introduction_to_Computational_Fluid_Dynamics/links/59ea182aa6fdccef8b08cb5b/Introduction-to-Computational-Fluid-Dynamics.pdf

[12] A. A. Rodriguez, R. P. Metzger, O. Cifdaloz, and T. Dhirasakdanon, "Description of a modeling, simulation, animation, and real-time control (MoSART) environment for a class of electromechanical systems," IEEE Trans. Educ., vol. 48, no. 3, pp. 359–374, 2005.

[13] H. Salehfar and S. and Trihadi, "Animated Monte Carlo simulation for teaching power generating system reliability analysis," IEEE Trans. Educ., vol. 41, no. 2, pp. 130–140, 1998.

[14] K.-H. Chang and C.-Y. Cheng, "Learning to simulate and design for structural engineering," in International Conference on Machine Learning, PMLR, 2020, pp. 1426–1436. Accessed: Aug. 16, 2024. [Online]. Available: http://proceedings.mlr.press/v119/chang20a.html

[15] S. Kumar and I. Milanovic, "Simulation-Supported Engineering Curriculum," in 2022 IEEE IFEES World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC), IEEE, 2022, pp. 1–6. Accessed: Aug. 09, 2024. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9996267/

[16] R. R. Gutierrez et al., "Combining hands‐on and virtual experiments for enhancing fluid mechanics teaching: A design‐based research study," Comput. Appl. Eng. Educ., vol. 30, no. 6, pp. 1701‐1724, Nov. 2022, doi: 10.1002/cae.22551.

[17] E. P. Douglas, M. Koro-Ljungberg, N. J. McNeill, Z. T. Malcolm, and D. J. Therriault, "Moving beyond formulas and fixations: solving open-ended engineering problems," Eur. J. Eng. Educ., vol. 37, no. 6, pp. 627–651, Dec. 2012, doi: 10.1080/03043797.2012.738358.

[18] A. Furnham and H. C. Boo, "A literature review of the anchoring effect," J. Socio-Econ., vol. 40, no. 1, pp. 35–42, 2011.

[19] J. J. G. Van Merrienboer, P. A. Kirschner, and L. Kester, "Taking the Load Off a Learner's Mind: Instructional Design for Complex Learning," Educ. Psychol., vol. 38, no. 1, pp. 5–13, Jan. 2003, doi: 10.1207/S15326985EP3801_2.

[20] M. E. Kiger and L. Varpio, "Thematic analysis of qualitative data: AMEE Guide No. 131," Med. Teach., vol. 42, no. 8, pp. 846–854, 2020, doi: 10.1080/0142159X.2020.1755030.