DEVELOPING SIMULATION-BASED COURSEWORK FOR ENERGY SUSTAINABILITY MODELLING

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ABSTRACT

The energy sector is the fastest-growing area in mechanical engineering, and it is optimal to prepare students for this growing niche of the job market. Modelling and simulation are increasingly used for system design in industry and research to finetune the design process and save on prototyping or testing costs. Correspondingly, energy modelling is an area of ever-growing relevance in the fields of mechanical and electrical engineering. However, there is a shortage of modelling and simulation programs in urban universities, which makes graduates of such schools less prepared for the energy job markets than their counterparts. To meet this need, a newly formed collaboration between the departments of Mechanical Engineering, Electrical Engineering and Computer Science, and Teacher Education at Cleveland State University is developing a graduate program concentrating in Modelling and Simulation in Sustainable Energy Systems (MS-SES) to better prepare students for increasing energy sustainability professional roles. Building information modelling is a topic of importance in the field of sustainability for future working professionals. Hence, one of the courses in this concentration will foster student learning by setting up and visualizing simulated energy models in buildings, using a combination of 3D modelling, fluid flow and temperature modelling, and virtual reality. This paper explores the design and learning outcomes of this educational project for students through a case study of a room in an office building with a heat source. The project-led learning plan is integrated with the fundamentals of modelling and simulation theory and data-driven modelling techniques such as machine learning. The results show promising integration of physics-based and data-driven models in support of education for energy sustainability in an extended range of domains from academia to industry.

Keywords: computational fluid dynamics, engineering education, energy sustainability, modelling and simulation, virtual reality.

1 INTRODUCTION

The energy system services sector within mechanical engineering has experienced the fastest growth in recent years. There is strong support from both industry and government in the domain; one example is a recent $369 billion for climate and clean energy provisions signed by President Biden in August 2022, the most aggressive climate investment ever taken by Congress [1]. It creates an unprecedented demand for a skilled workforce familiar with emerging technologies in sustainable energy systems where computer modelling and simulation are essential skill sets. Modelling and simulation (MS) are being increasingly used in industry for product development, system design and retrofitting, and risk assessment. Hence, they are consequently becoming a prerequisite for testing, prototyping, and commissioning. There have been increasing efforts in the last decade in establishing energy/environmental sustainability programs at universities [2], exploring energy sustainable development practices, and organizing workshops/sustainability days where universities and industries get together to share their findings, strategies, and plans. However, there is a shortage of MS programs in individual disciplines that benefit from the increasing

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trend of digitalization, the Internet of Things, artificial intelligence, big data, and complex energy-saving engineering systems. This shortage becomes more significant in urban state universities, where diverse and underrepresented students choose to study. The Modelling and Simulation in Sustainable Energy Systems (MS-SES) program at Cleveland State University (CSU) is an example to address this need, and take the current efforts to another level where university energy/sustainability projects' outcomes can be integrated into the industry and society needs; this will also satisfy the need of studying an extended range of scenarios to obtain an optimum performance-cost solution. In addition to current graduate-level courses, four new ones are being developed and existing project courses will be enhanced to align with the MS-SES program (Fig. 1). Student-centred, diverse, and career-oriented goals are the core of developing flexible curricula and certificate programs in support of students' success. The program's sustainability will be achieved through continuous evaluation, best teaching practices implementation, and active participation of academics and industrial partners. Four major areas of fundamentals, modelling, simulation, and verification and validation are pursued in the developed courses.

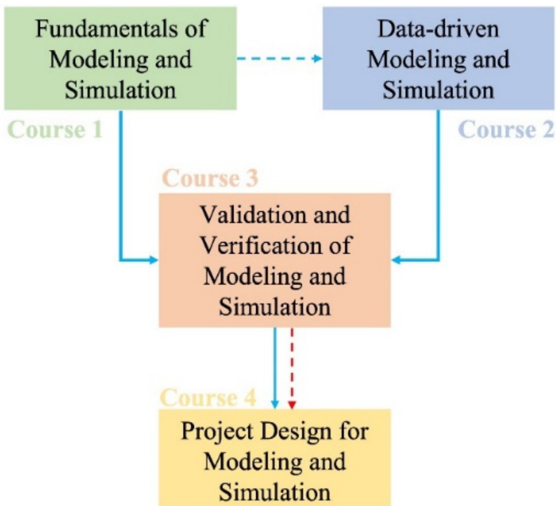

Figure 1: Relationship between four courses in the MS-SES program.

This paper aims to demonstrate the preliminary results of the implementation of these four areas through a case study within building energy modelling developed in the MS-SES program. The case study will be under 'Course 4' in Fig. 1; the topic will be introduced to students from the beginning of the program. They will implement the fundamental knowledge and MS skills in the previous courses on this topic (as a case study). Section 1.1 describes the current practice of conducting computational fluid dynamics (CFD) for building information modelling (BIM) and the need for simplified visualization tools. Section 1.2 provides a review of enhanced visualization techniques and concludes with the current MS-SES program computational facility and resources. Section 2 describes the case study and the implementation of the proposed methodology. Section 3 will present the results. Finally, the conclusion provides a summary of the case study and describes future steps in both the MS-SES program and the BIM project.

1.1 Educational use of CFD simulation for energy sustainability modelling

Energy systems' long-term sustainability requires obtaining multiscale (spatial and temporal) mechanical, design, operation, and lifecycle analysis. Examples within BIM include building occupant behaviours, building energy equipment and system design and operations, equipment energy demand, energy production, grid and/or district energy distribution, and operations with mixed (renewable and non-renewable) energy sources. There are significant uncertainties and risks in the new design and retrofitting of such energy systems and for high-risk or dangerous situations, including cybersecurity issues where experiments, prototypes, and demonstrations are not realistic. MS of those energy systems together with parametric study and expert/user input data will generate alternative and larger data sets that will lead to data-driven discovery for the key stakeholders to make decisions. A multidisciplinary learning approach can be common to many disciplines, such as health science, bioengineering, natural science, and business, for the future development of MS programs in their respective fields.

One example in BIM is visualizing internal airflow/temperature fields when the internal design or environmental conditions change. CFD simulations have been used and taught in engineering programs extensively to study the changes in internal and external physical properties such as pressure, temperature, and airflow when either boundary conditions or design parameters change. However, like some of the commonly used building energy modelling tools such as EnergyPlus, CFD simulation outputs either require domain-specific expertise for understanding, interpreting, and explaining or include complex datasets that need further post-processing to visualize the results. While these aspects are addressed in multiple CFD tools such as ANSYS or OpenFOAM, they are still very engineering-oriented and might not be used by professionals out of the domain, which might result in cognitive overload. A research study by Zhu et al. [3] demonstrated the combination of CFD and mixed reality (MR) in building renovation design. Similarly, another study by Fukuda et al. [4] successfully utilized BIM, CFD, virtual reality (VR), and augmented reality (AR) in a home construction project. After the BIM stage, CFD analysis was used to determine the air temperature profile and redesign internal boundaries for optimal airflow distribution. VR and AR were then used to show the client the project's proposed outcomes, after which construction began. In these cases, the client or decision-makers might not need any fluid mechanics or building energy analysis background to understand the impact of design change. It is therefore important to familiarize students and engineers with visualization techniques to prepare them for the future job market and make them competitive candidates for jobs in the energy modelling domain. Little is known about the educational use of VR with CFD simulations and the selection of key factors in design, development, and evaluation phases are still undergoing [5]. Recent literature shows that coupled BIM-CFD-VR approach will help students with no knowledge of BIM, fluid mechanics, and computer engineering to visualize the impact of design or environmental conditions on airflow/temperature distribution; for students at the graduate level, the proposed approach will help them to identify and resolve potential issues due to either design or environmental changes more effectively. The complementary component of this approach is scientific visualization, beyond CFD post-processing visualizations; this is elaborated in Section 1.2. Currently, to the best knowledge of the authors, this complementary component neither has instructional design nor supportive educational content and has been mainly the focus of research.

1.2 Enhanced visualization: Virtual reality, mixed reality, and augmented reality

A traditional display provides a two-dimensional view to the users via a computer monitor, a TV, or a projector screen. There is a spectrum of enhanced visualization techniques, ranging from virtual reality, and mixed reality, to augmented reality. In this section, a brief introduction of techniques together with an overview of currently available commercial products are provided. Moreover, an outline of the development platforms and some open research issues related to enhancing visualization are described.

The most authoritative writing on enhanced visualization is by Milgram and Kishino [6]. They used the term 'mixed reality' to refer to the spectrum of enhanced visualization techniques. Several different terms have been used in the literature to refer to some forms of enhanced visualization, including VR, AR, MR, and augmented virtuality (AV). The relationship is illustrated in Fig. 2 [6]. At the two ends of the spectrum are the physical environment and the virtual environment. The physical environment refers to the display of the physical environment as it is without any modification. A virtual environment refers to the display of a completely digitally constructed environment that has nothing to do with the actual physical environment the user is residing in. The display of a virtual environment is often referred to as virtual reality. In the middle of the spectrum, the display would contain elements of physical and environment as well as elements of virtual environment; hence, it is referred to as mixed reality. If the display is mostly about the physical environment, it is sometimes referred to as augmented reality. On the other hand, if the display is mostly about the virtual environment, it is referred to as augmented virtuality. That said, the term augmented virtuality is rarely used in the literature. Instead, VR, AR, and MR are often interchangeably used.

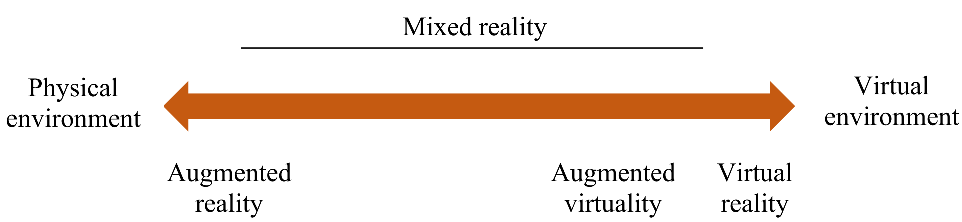

Figure 2: The spectrum of enhanced visualization [4].

The spectrum of enhanced display is accomplished via two important components: (1) content construction, and (2) visualization device. The content construction of the physical environment can be easily accomplished using a video camera to capture the live feed or using pre-recorded video of the physical environment. MR or AR can be accomplished by adding virtual objects on top of the rendered physical environment scenes, which requires accurate knowledge of the objects in the physical environment. The latter can be done via computer vision analysis of the physical scenes, or via three-dimensional (3D) sensing. MR or AR could also be achieved by composing some information regarding the physical environment into virtual scenes. The construction of virtual content usually requires 3D modelling software such as 3DS Max from Autodesk, the open-source Blender, and 3D software development platforms such as 3D Unity. 3D modelling software is needed to develop 3D virtual objects and scenes and to allow user interaction with the 3D scenes.

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Visualization devices vary significantly. The content of the spectrum of enhanced visualization may be displayed via a traditional computer monitor, TV, or project screen. This could lose the 3D immersion of the content. A costlier and more sophisticated device could be used for creating an immersive environment, such as the Cave Automatic Virtual Environment (CAVE) system which consists of multiple projectors and semi-closed surrounding project screens. In recent years, cheaper options are becoming available in the form of commercially available VR headsets, such as Apple Vision Pro, HTC VIVE, Oculus, and Windows Mixed Reality Headset. MR devices would allow virtual objects superimposed on top of the physical environment, which could be highly useful in specific contexts. Google Glass was the first product along this line. Unfortunately, it is no longer in production. Microsoft HoloLens is the only consumer-grade untethered MR device. HoloLens achieves MR via sophisticated depth sensing of the physical environment and holographic display where a user could see both the physical environment as well as digital objects (referred to as holograms) rendered in three dimensions holographically. HoloLens is also capable of recognizing a limited set of finger-based gestures that can be used for command and control. In addition, mobile phones or tablets can be used to achieve immersive VR and AR with the help of additional gadgets, such as a VR headset (for virtual reality) and a quick response (QR) code sticker (for augmented reality). Numerous studies have reported the usefulness of using various forms of enhanced visualization [7]–[11] with an overall positive attitude of students [8]. However, there are also reports on implementation challenges and the negative side effects of using head-mounted displays and virtual reality goggles, including dizziness and tiredness [12].

As part of the MS-SES program, the team has established a cutting-edge MS lab. This state-of-the-art facility is equipped with high-performance workstations, simulation software (e.g., ANSYS and Autodesk CFD), VR headsets, and VR software (e.g., Unity). With this high-end lab, the team can effectively utilize advanced mesh generation techniques and conduct moderate-level simulations. A seamless modelling, simulation, and visualization pipeline is created that greatly enhances student learning outcomes. By directly mapping the output of simulations onto virtual environments, students gain a unique opportunity to witness the impact of MS accuracy on actual problem scenarios. This immersive experience not only deepens their understanding but also cultivates a strong grasp of the practical implications. By leveraging VR, students will be empowered to explore the relationship between simulations and real-world challenges, ultimately preparing them for the complexities of engineering practices.

2 CASE STUDY

Students are expected to have basic knowledge of mechanical engineering core domains before enrolling in the MS-SES program. They will be focusing on MS fundamentals and skills and will apply them to different energy-/sustainability-related real-case scenarios; this approach follows the civic-engagement-learning strategy. This section describes one possible BIM case study with a focus on developing a coupled BIM-CFD-VR to visualize airflow/temperature in a room.

An experimental study seeking to investigate the effect of a radiant heat source on the air temperature and flow fields within a room subjected to displacement ventilation was carried out by Li et al. [13]. Gilani et al. developed a CFD model from Li et al. [13] to explore the accuracy of various CFD turbulence models [14]. Khalesi and Goudarzi used Li et al. [13] and Gilani et al. [14] to develop a CFD model to explore the efficacy of smart windows for indoor thermal comfort [15]. The studied case study in this work uses these CFD papers for computational setup and experimental work for validation. The BIM-CFD-VR instructional design process to study and visualize the airflow/temperature distribution in an office room follows three main steps illustrated in Fig. 3. This process covers the entire cognitive spectrum in Bloom's taxonomy of learning and multimedia learning principles to enhance engineering students' technical skills and competencies.

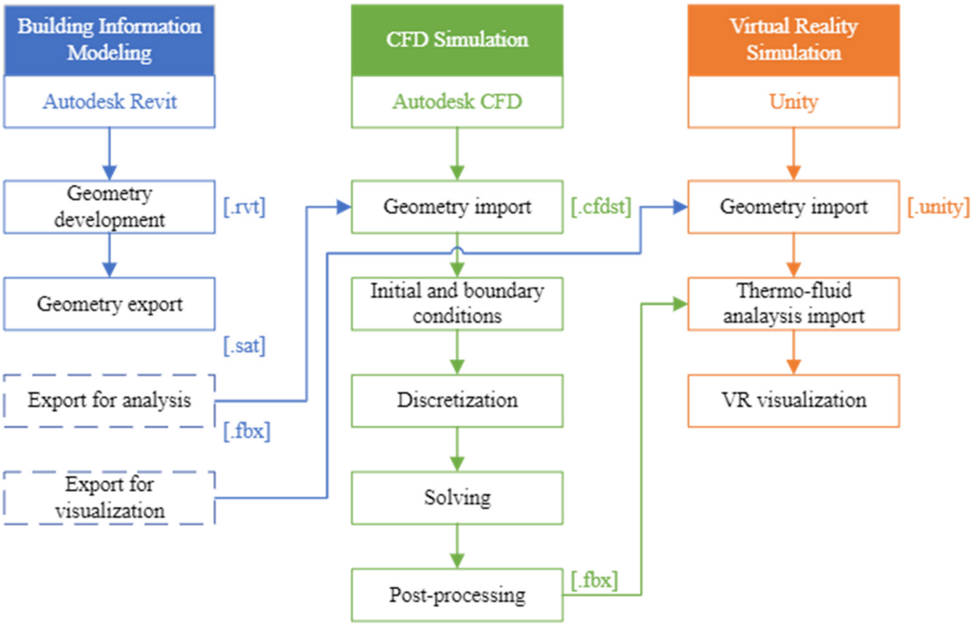

Figure 3: BIM-CFD-VR coupled process flowchart.

The first step is generating the geometry. In this paper, Autodesk Revit is used to design a room with a heat source; this is a real-life multiphysics example with a good overlap with existing engineering curricula. As elaborated in Section 3 on why this software was selected, students are expected to have basic skills in computer-aided design (CAD) tools and can use other CAD software to create geometry. The room dimensions (Table 1 and Fig. 4) and physical properties follow the earlier experimental room study [13]. A floor-level perforated air inlet duct located on the south wall and close to the floor supplied low-velocity cooling air (at 16°C) to the room. An outlet duct located on the east wall and close to the ceiling carried exhaust air out of the room. A 300 W heat source within the room, suspended 0.1 m above the floor and 2.75 m away from the air supply inlet. The geometry file (with '.rvt' extension) is exported with '.sat' and '.fbx' extensions for CFD and VR steps, respectively.

Table 1: Full-scale experiment dimensions.

Region	Dimensions (m)
Room dimensions (width × length × height)	3.60 × 4.20 × 2.75
Inlet duct dimensions (width × height)	0.45 × 0.50
Outlet duct dimensions (width × height)	0.52 × 0.22
Heat source dimensions (width × length × height)	0.30 × 0.40 × 0.30

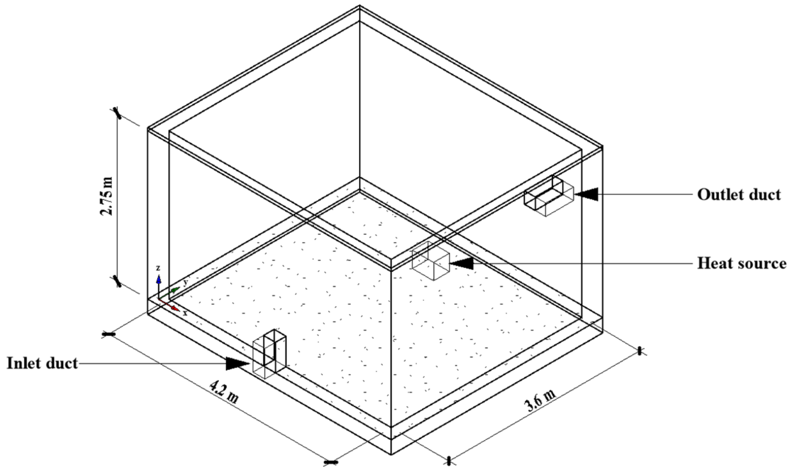

Figure 4: Schematic of the studied room with an inlet, outlet, and heat source.

The second step is calculating airflow fields and temperature distribution in the room using a CFD simulation. This step is taught under ‘Course 1’ in the MS-SES program in Fig. 1. Students will learn the fundamentals of MS of physical systems and physics-based modelling software such as ANSYS, OpenFOAM, and Autodesk CFD. Following the active learning strategy, students will follow a combination of reading, critical thinking, group discussions, and problem-solving to explore different MS strategies of a real-world problem; in this case study, it will be how to accurately obtain the airflow and temperature distribution inside a room with a heat source.

The computational setup that includes the materials, initial and boundary conditions, discretization, and turbulence model are shown in Table 2. The ceiling, floor, and walls have a uniform U-value of 0.36 W/m^2K, and the west wall has a U-value of 0.15 W/m^2K. Students will learn validation and verification of MS in ‘Course 3’ in Fig. 1 and use those skills to run a series of mesh sensitivity check to monitor the changes in outlet temperature to assure the quality of the selected mesh. The best mesh, a fine mesh with 1.9 million cells, was used for the solver. An elaborated limitation of using Autodesk CFD is discussed in Section 3.

The third step is generating VR visualization. This step is taught under ‘Course 2’ in Fig. 1. Students will learn in-depth fundamentals of machine learning and data analytics that will be used in solving engineering applications. Students are introduced to the visualization of physics-based modelling tools in Course 1. They will learn data visualization skills and tools in course 2. Hence, they can use the exported geometry from Autodesk Revit and CFD results in the post-processing (including airflow and temperature distribution) as inputs to VR simulation in Unity.

3 RESULTS AND DISCUSSION

Coupled BIM-CFD-VR approach enables visualizing CFD simulation post-processing results without the need of understanding the complexities involved in generating airflow or temperature fields. This becomes more important when students, architects, and decision-makers are interested in understanding natural/mechanical ventilation and thermal comfort changes due to environmental or design variations. The heat source in this work could be adjusted to mimic either a person or an object with a known temperature.

Table 2: CFD Computational setup.

Materials	
Walls and ceiling	Gypsum board
Floor	Cement
Heat source	Aluminium
Inlet duct, outlet duct and room interior	Air
Boundary conditions	
Inlet air velocity	0.1 m/s
Inlet air temperature	16°C
Outlet air pressure	0 Pa
Wall, floor, and ceiling temperature	24°C
Floor, ceiling, north/south/east wall U-values	0.36 W/m^2K
West wall U-value	0.15 W/m^2K
Heat source surface temperature	32°C
Heat source	300 W
Mesh and solver	
Number of cells	1.9 million
Turbulence model	k-ε

After conducting a grid sensitivity check, the solution from the selected mesh is validated with both experimental and computational reference works. The output temperature of the room was monitored for validation purposes and the final Autodesk-CFD simulation converged for all desired variables and resulted in an acceptable engineering error compared to the experimental work. The temperature distribution result on the middle plane is shown in Fig. 5(a), with the heat source shown in red at 32°C. The airflow streamlines are shown in Fig. 5(b), with stronger airflow between the inlet and heat source and between the heat source and outlet; the rest of the room does not experience strong airflow with the current inlet airflow and location of the heat source.

This paper just shows one possible location of the heat source, as a demonstration case study. More CFD simulations are carried out to move the heat source around the room and generate a dataset that traces the airflow field from the inlet to the outlet. These simulation results are inputs to the VR visualization tools. More specifically, the floor plan in the simulation is divided into a 4 × 4 grid and three levels along the height of the room with a total of 48 cells. The heat source is assumed to be in any of the cells and could move from one cell to another adjacent cell. One CFD simulation is conducted for every possible heat source location. Hence, a total of 48 CFD simulations are conducted beforehand. The user interface will provide a control for the user to specify the initial location of the heat source, and then move it to any of the adjacent cells. The user would then view the resulting CFD simulation to see the differences when the heat source moves around the floor. This could be regarded as the first step towards data-driven modelling and simulation because the simulation now would become interactive. Similar CFD simulations with changing the boundary conditions (e.g., inlet/outlet properties such as mass flow rate and temperature) will yield more input data for this interactive platform. Finally, a complete loop of BIM, CFD, machine learning, and VR visualization will yield a comprehensive yet simple-to-understand tool for students, architects, and decision-makers.

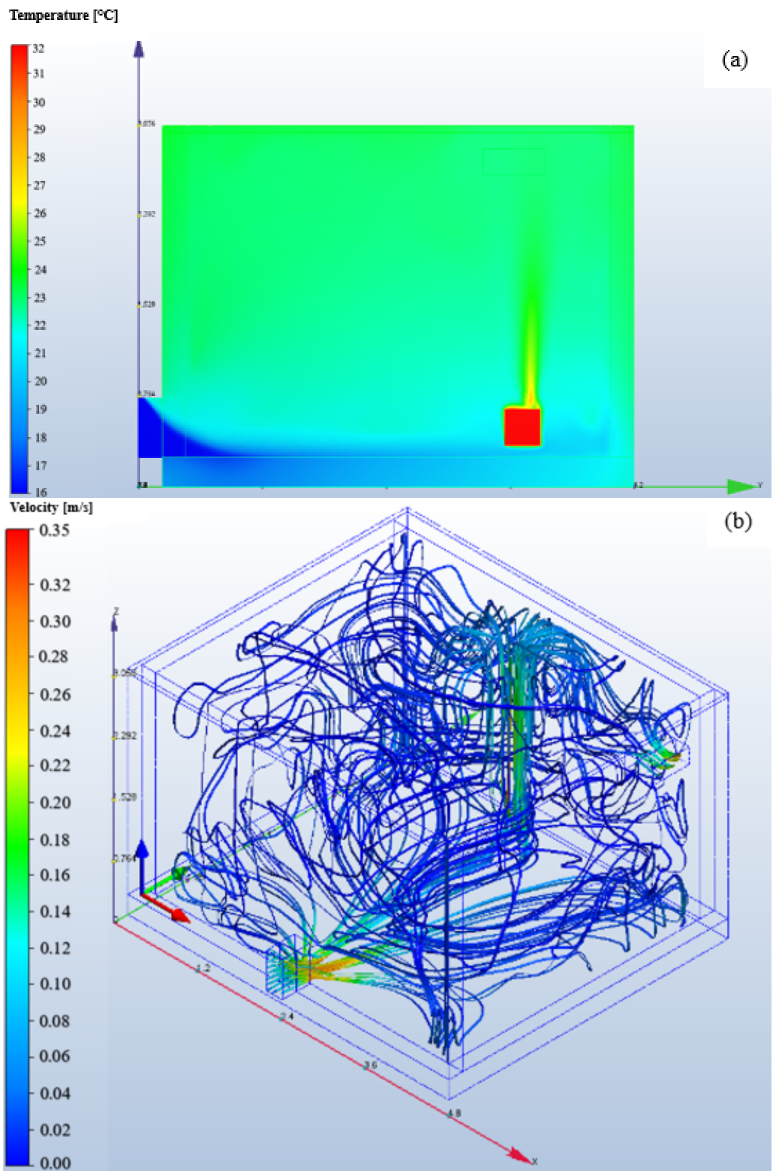

Figure 5: CFD simulation results. (a) Temperature contour; and (b) Airflow distribution.

There has been an increasing trend in the past decade in developing energy sustainability curricula in universities and university networks. New concepts such as energy metaverse require a faster pace in developing educational content to address the growing demand for skilful engineers. The results of this case study show the possibility of working on energy sustainability and integrating digitalization into training in parallel through developing multidisciplinary programs, like the MS-SES at CSU. This is believed to be the next step in supporting energy/environmental sustainability programs at universities.

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The project comes with multiple challenges. A major challenge comes from coupling multiple software that requires high interoperability between them [6]. Currently, due to existing complexities in each of the three steps followed in this paper, they cannot be carried out on a single platform. Hence, all the possible coupling solutions need to confirm the imported, exported, and data post-processing files' compatibility. To mitigate this challenge in this paper, Autodesk software was used for the first two stages. This mitigated the interoperability concern and Autodesk offer free student license which can be a big plus for education and training. However, the lack of high-fidelity CFD modelling capabilities (compared to OpenFOAM or ANSYS) impacts simulation accuracy, especially when the problem becomes more complex. It was found that the Autodesk-CFD package is prone to crashing which requires rebooting both the software and computer. Hence, either new versions of the software should address this or alternative CFD simulation platforms such as OpenFOAM should be considered. There are reported challenges considering the human factor including usability, simulator sickness, and scalability. Most of these challenges are either reported as primary findings or obtained from a limited group of participants [8]. Hence, these challenges are subjects of current and future studies when considering the integration of enhanced visualization techniques for education.

4 CONCLUSION AND FUTURE WORK

A new graduate program concentrating in MS-SES is formed at CSU through collaboration between the departments of Mechanical Engineering, Electrical Engineering and Computer Science, and Teacher Education. This program aims to benefit digitalization, artificial intelligence, and information technology, to take the existing energy/sustainability programs to the next level, and better prepare students for future related professional roles. The topic of MS using innovative coupled pipelines, from design to enhanced visualization, is quite new in the system of higher education and industry. This paper presented a case study of a room in an office building where students, architects, and decision-makers can visualize CFD simulations post-processing in a VR environment. Generated geometry in Autodesk Revit was used for both Autodesk CFD and Unity VR visualization. The CFD model was validated with experimental and computational reference literature. The validated model results were inputs to Unity to visualize CFD results, namely the temperature stratification and airflow distribution in the office room. This implementation demonstrated the value of increasing interest in using scientific visualization tools in energy sustainability applications.

The BIM-CFD-VR process showed a promising alternative to current individual and (in some cases) complex approaches in energy sustainability education, especially when used for teaching or by users out of the knowledge domain. However, as suggested in the literature, certain domains such as the overall workflow beyond BIM application, human factor evaluation, and data interoperability need improvement [5]; this is one of the ongoing areas of study and development in the MS-SES program that can be achieved through experimental testing at the MS lab in this program.

The generated geometry contained basic elements of a room in an office building to reduce the uncertainties and computational cost of the CFD simulation. The future work should follow a step-by-step process where complexity increases, e.g., including cabinets as cuboid boxes that mimic a real office room. It also should explore Autodesk's (and similar tools) capabilities and limitations in handling more complex scenarios and potential alternatives that can address them while keeping acceptable interoperability.

The program is in the early stages of development. However, a course evaluation plan is developed and will be implemented. The assessments conducted in most of the similar works have been superficially reported and require more profound discussions. A mixed methods approach is used to evaluate the program, following recommendations for scientific research in education by the National Research Council (NRC). Both quantitative and qualitative data will be collected to test hypotheses of the impact of innovative course design on student outcomes, document the processes of course development and implementation, and gain an in-depth understanding of faculty and student experience throughout such processes. Pre-tests, post-tests, and rubric-based project assessments will be used to measure student mastery of basic course concepts, proficiency in common MS tools, and abilities to abstract, model, simulate, and support decision-making for real-world sustainable energy systems. Pre- and post-surveys will be administered to examine changes in student beliefs and attitudes towards the course, the content, and MS applications (e.g., self-efficacy, interest, perceived value). Qualitative data will be in the form of recordings of project meetings and guest presentations, meeting memos and transcripts, documents related to the processes of course development and project implementation, lab observations, and semi-structured interviews of students and faculties involved in the project. The data collection and analysis are consistent with the Accreditation Board for Engineering and Technology (ABET) assessment framework with emphasis on the following elements: performance indicators, educational strategies, where formative data are collected, where summative data are collected, methods of assessment, time of summative data collection, and threshold for performance. For continuous project improvement, the assessment results, actions, and second-cycle results will be documented and reported.

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