Buildings & Cities

Integrating computational fluid dynamics into introductory architectural education

RESEARCH

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ABSTRACT

This study designed, implemented and evaluated a hybrid course integrating thermo-fluid-dynamics lectures with hands-on computational fluid dynamics (CFD) training for about 100 first-year architecture students in Japan. The course comprised 14 sessions: 10 lectures, three CFD training sessions and a review/feedback session. Students received feedback from the instructor and teaching assistants at an early checkpoint. Additional support included lecture-linked training materials, peer comparison and a whole-class review of common errors. The evaluation relied mainly on questionnaire responses about students' self-rated understanding, interest and difficulties. Self-rated understanding increased after the CFD training, particularly for simulation set-up and interpretation. Over 90% of students reported greater interest in the built environment and a heightened awareness of thermal and airflow design. Reported difficulties shifted from software operation in the first practical session to boundary-condition-setting and visualisation in later sessions. The aligned lecture–training approach appears feasible at the introductory level and is associated with improved perceived understanding and engagement; as the findings rest on students' perceptions, they are interpreted as changes in perceived learning rather than as causal effects.

PRACTICE RELEVANCE

This course provides an example of how CFD can be taught to beginning architecture students. The findings suggest four points for course design: (1) aligning thermo-fluid-dynamics lectures with hands-on CFD on shared, simplified tasks makes abstract physical concepts visible and raises students' perceived understanding and interest; (2) beginners' difficulties shift from software operation to boundary conditions, modelling and result interpretation as tasks become open-ended, so support should be staged accordingly; (3) an early checkpoint with instructor and teaching-assistant feedback, lecture-linked training materials, peer comparison, and whole-class review of common errors together help students understand the lecture content and address these difficulties; and (4) early teaching of airflow and heat transfer may help students use CFD to assess airflow and thermal conditions in later design courses, with the long-term goal of supporting designs that reduce energy use and improve thermal comfort and indoor air quality.

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1. INTRODUCTION

Following the adoption of the United Nations resolution entitled Transforming Our World: The 2030 Agenda for Sustainable Development (UNGA 2015) and the Paris Agreement (UNFCCC 2016), demand has grown across various sectors to promote a sustainable society. The building sector in particular holds significant responsibility, given its broad impact on the environment and human life (UIA 2022a, 2022b). A key approach in this field is the design and promotion of sustainable buildings (Wen *et al.* 2020; WGBC 2016).

To promote sustainable buildings, two critical actions are necessary: (1) increasing the demand for sustainable buildings in the market; and (2) designing and supplying buildings that satisfy this demand. Environmental performance-assessment tools such as the Building Research Establishment (BRE) Environmental Assessment Method (BREEAM) (BRE n.d.), Leadership in Energy and Environmental Design (LEED) (USGBC n.d.) and the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (IBECs n.d.) play an essential role in raising awareness among consumers and highlighting the value of high-performance buildings (Eichholtz *et al.* 2010; Fuerst & McAllister 2011; Khashe *et al.* 2015; Murakami *et al.* 2014; Takada *et al.* 2020). Meanwhile, to design sustainable buildings effectively, building performance simulation (BPS) has been increasingly utilised from the early design stages, enabling designers to predict and optimise a building's impact on both people and the environment (Augenbroe 2002; Clarke & Hensen 2015; Wang & Zhai 2016).

The field of BPS has evolved since the 1960s, transitioning from research-focused tools for energy and thermal load analysis to more accessible software platforms that both practitioners and students can use (Haves 2011). Today, BPS is widely used to optimise a range of design parameters (Brozovsky *et al.* 2022; Guo *et al.* 2022; Kwok *et al.* 2022; Sharif & Hammad 2019; Weerasuriya *et al.* 2019), and there is a growing infrastructure supporting its integration into design workflows (Clarke 2015). However, realising the full potential of BPS depends on educating users about its theory, applications and limitations.

Simulations with relatively lower computational demands, such as those for energy consumption or lighting, have long been utilised in architectural education, and their educational effects and associated challenges have been investigated in various contexts (*e.g.* Hand 1993; Hanna 1996; Kim 2020; Mavromatidis 2018; Roberts & Marsh 2001; Soebarto 2005). In contrast, computational fluid dynamics (CFD), which involves complex and computationally intensive simulations of airflow and heat transfer, has been less frequently incorporated in educational curricula, despite its potential to deepen understanding of the physical processes that shape indoor environments. The United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Union of Architects (UIA) published the 2026 UNESCO–UIA Charter for Architectural Education. The Charter includes technical knowledge needed for indoor comfort and environmentally responsible design among its educational objectives (UIA 2026). CFD-based learning can contribute to these objectives by helping students understand how airflow and heat transfer affect indoor thermal conditions. Previous studies have examined students' written reflections on BPS education (Bohm 2025) and alumni survey responses about learning outcomes and how the learning was used in professional work (Passe 2020).

CFD-based training has been introduced in chemical, mechanical and aeronautical engineering (Adair *et al.* 2014; Aung 2003; Berg *et al.* 1999; Hu *et al.* 2008; Spall & Hailey 2000). In architectural education, Tsou (2001) developed online lessons that combine explanations of airflow principles with CFD exercises using predefined simulation models. Introducing CFD requires class time and teaching support for learning both physical principles and simulation procedures. However, advances in user interfaces, automation and predetermined simulation conditions have made CFD software increasingly accessible. This democratisation of tools has opened new opportunities to integrate CFD into the early stages of architectural education.

However, these advancements also risk the 'black-boxing' of simulations, wherein users rely on software defaults without understanding the underlying theory, causing them to misinterpret the results (Soebarto 2005). To address this problem, theoretical instruction can be combined with

CFD exercises that link simulated airflow to physical principles (Tsou 2001). In BPS education, experiential learning involves using concepts in simulation tasks, reflecting on the results, and applying what has been learned in later tasks (Beausoleil-Morrison & Hopfe 2015).

This study examines a hybrid course that integrates thermo-fluid-dynamics lectures with hands-on CFD practical training for about 100 first-year undergraduate architecture students with little or no prior knowledge of fluid dynamics or CFD. The study examines the use of CFD to teach thermo-fluid principles in a required first-year architecture course. Students' self-reported understanding, interest and difficulties were used to examine the course and identify areas where beginners may need more support. Here, 'beginners' refers to architecture students beginning to learn thermo-fluid principles and CFD.

In Japan, architecture is taught as an integrated discipline combining architectural design, structural engineering and environmental engineering within one undergraduate programme. The course examined in this study was offered within such a programme. These students have not yet specialised, so introducing hands-on CFD at this stage differs in purpose and audience from CFD instruction in dedicated engineering programmes, and offers an informative setting for cultivating simulation literacy early in a design-oriented curriculum. Learning about airflow and heat transfer through CFD in the first year may help students interpret simulation results more effectively in later architectural design courses.

The course design employs several instructional strategies, including staged analysis tasks, group-based comparison and exploratory assignments, all of which are intended to support students' engagement with CFD and their application of theoretical concepts. These instructional choices aim to reveal how students at the introductory level perceive the value of CFD, where they encounter difficulties and what resources support their successful engagement with the tool.

Specifically, this study investigates the following research questions (RQs).

- RQ1: How does hybrid CFD education affect students' understanding of thermo-fluid dynamics concepts?
- RQ2: How does hybrid CFD education influence students' intellectual curiosity toward and interest in thermo-fluid dynamics concepts?
- RQ3: How do specific features of practical training enhance or hinder learning for beginners?

In this study, the CFD practical training was designed to help beginners understand the workflow and interpretation of simulations, rather than to validate numerical prediction accuracy. By conducting questionnaire-based evaluations, this study provides new survey-based insights into the educational effectiveness of CFD in architectural education. The results contribute to ongoing discussions about simulation literacy, sustainability education and curriculum design in architecture-related disciplines.

2. COURSE OUTLINE

The course content was delivered uniformly to all enrolled students, and instructional elements were not withheld for research purposes. The selected CFD tasks and physical models were intentionally simplified to fit class-time and beginners' prerequisite knowledge, while retaining an authentic workflow that supports simulation literacy. This section outlines the structure and instructional design of the hybrid CFD course, which was developed to address the above-mentioned three RQs.

2.1 WEEKLY SESSION TOPICS

A hybrid course structure was used to maximise the educational benefits by combining the complementary strengths of lectures and practical training. Lectures alone tend to promote passive learning, and students' understanding can vary depending on their interest in the content. Integrating lectures with hands-on training enables students to visually grasp the connection

between physical phenomena and buildings, thereby promoting active learning. Practical training alone, especially in analysis, can hinder students from connecting theoretical concepts to analytical procedures. Therefore, incorporating lectures can prevent the 'black boxing' of analytical methods. This design supports RQ1 by reinforcing students' theoretical understanding through hands-on application. It also contributes to RQ2 by stimulating curiosity through visualisation of physical phenomena in building contexts.

Table 1 outlines the structure of the course. The course comprised 10 lecture sessions, three practical training sessions (sessions 11–13), and one review/feedback session (session 14). Each session lasted 100 minutes. Sessions 1–10 consisted of whole-class lectures on thermo-fluid dynamics and the numerical principles used in CFD. This sequence was chosen because the practical tasks required students to combine concepts from several lectures, including fluid flow, heat transfer, discretisation and boundary conditions. For example, students applied discretisation from session 6 when generating meshes, and used boundary conditions and steady-state analysis from session 7 when setting up models and interpreting results. The three practical sessions progressed from guided exercises to analyses planned by the students. Session 14 included a review of exemplary work, common errors, and their solutions to help students reflect on their model settings and interpretation of results. Lecture handouts and references to relevant books and websites were provided and students completed exercises at the end of the lecture sessions to reinforce the content.

Table 1: The course's weekly sessions and topics.

SESSION		MAIN TOPIC
1	Lecture	Guidance
2		Zeroth and first laws of thermodynamics
3		Forms of heat transfer (conduction, convection and radiation) and types of fluid flow (laminar and turbulent flow)
4		Interpretation of system and control volume
5		Three governing equations in fluid dynamics
6		Significance and typical discretisation methods
7		Steady- and unsteady-state analyses, setting boundary conditions and modelling near the surface of a wall
8		Thermal circuits
9		Heat transfer inside walls (heat transmission)
10		Significance and overview of computational fluid dynamics (CFD)
11	Practical training	Analysis dealing only with airflow
12		Combined thermal and airflow analysis
13		Analysis in which students are free to set contents (object, conditions, *etc.*)
14	Review/feedback	General review and feedback on the practical training in session 13
–	Final examination	Final examination covering the lecture and practical training content

2.2 PRACTICAL TRAINING AND CFD ANALYSIS TOPICS

The practical training was designed to help first-year students understand what CFD is, how simulations are set up and interpreted, and why airflow and thermal phenomena matter in buildings—and, ideally, to motivate them to study the subject further on their own. The guided exercises therefore used simplified, common tasks within limited class time. Advanced issues such as turbulence-model selection, mesh dependence and detailed verification were introduced only at a conceptual level. The priority at this introductory stage was for students to complete an end-to-end workflow and build physical intuition. In architectural design studios from the second year onward, students use environmental assessment, measurement and simulation to develop their design proposals. CFD is used to evaluate airflow and thermal conditions associated with these proposals. Some students also use CFD in their fourth-year graduation design projects.

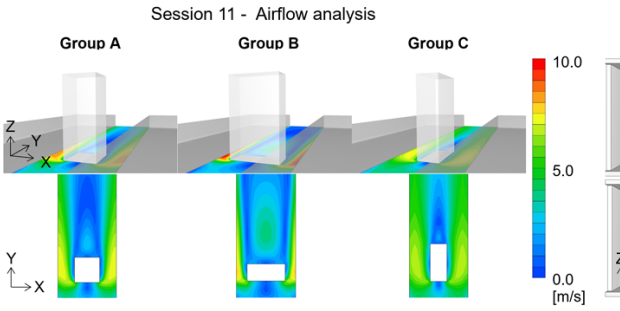
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Practical training involving CFD analysis was conducted in sessions 11–13. The training progressed in three stages that aligned with students' learning levels: basic airflow analysis (session 11), thermal-airflow analysis (session 12) and applied analysis (session 13). This progression was designed to support students in deepening their understanding (RQ1, RQ2) and to identify challenges encountered at different levels of complexity (RQ3).

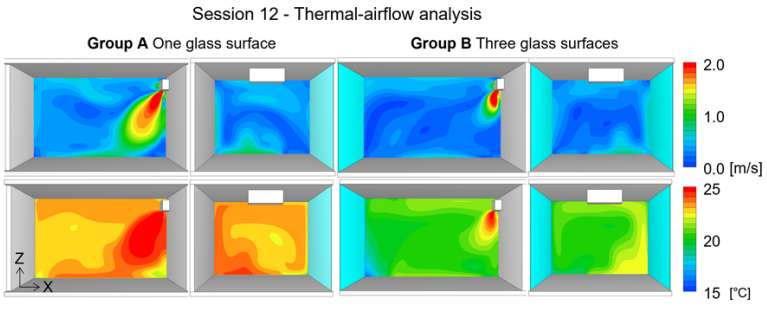
Figure 1 shows the practical training and analysis topics in sessions 11 and 12. In session 11, students performed an airflow analysis of the wind environment around a high-rise building. In session 12, they performed a thermal-airflow analysis of a room with an air-conditioner operating in winter. Both sessions focused on visualising and interpreting simulation results with the aim of understanding physical phenomena related to airflow and thermal dynamics. These analyses were required to reach a steady state, with the convergence criterion set at 1.0×10^{-4}. Here, steady state means that the simulated flow and temperature fields do not change over time, while convergence means that the iterative numerical solution meets the stated criterion. Radiant heat was excluded from the thermal analysis in order to reduce the simulation time.

Figure 1: Analysis topics covering an outdoor high-rise wind environment and an indoor air-conditioned room.

Note: These examples were used as common instructional tasks for visualising airflow and thermal phenomena; figures are not presented as validated predictions of specific outdoor or indoor environments.



	Regular rectangular column	Rectangle long in the X-axis direction	Rectangle long in the Y-axis direction
	60 m (X), 60 m (Y), 150 m (Z)	90 m (X), 40 m (Y), 150 m (Z)	40 m (X), 90 m (Y), 150 m (Z)
Analysis area	800 m (X), 800 m (Y), 400 m (Z)		
Pressure-correction method	SIMPLE algorithm		
Turbulence model	Standard k-ε model (high Reynolds) k=1e-10 m^2/s^2, ε=1e-10 m^2/s^3		
Analysis type	Steady state analysis		
Discretization scheme for advection term	First-order upwind scheme		
Total number of cells	Approx. 1,000,000		
Flow boundary condition – Inflow	Ymin power law, velocity: 3.0 m/s (standard height: 10.0 m)		
Flow boundary condition – Outflow	Ymax total pressure: 0 Pa		
Wall boundary condition	Xmin, Xmax, Zmax: free slip, Other surfaces: logarithmic law		



		Group A One glass surface / Group B Three glass surfaces
Analysis area		4,200 mm (X), 3,200 mm (Y), 2,700 mm (Z)
Pressure-correction method		First-order upwind scheme
Turbulence model		Standard k-ε model (high Reynolds) k=0.3086 m^2/s^2, ε=8.048 m^2/s^3
Analysis type		Steady state analysis
Discretization scheme for advection term		First-order upwind scheme
Total number of cells		Approx. 300,000
Flow boundary condition	Inflow	Outlet surface of air conditioner outlet area: 0.03 m^2, airflow rate: 600 m^3/h, airflow temperature: 27.0 °c
	Outflow	Outlet surface of air conditioner inlet area: 0.16 m^2, surface pressure: 0 Pa
Heat boundary condition	Xmin, Ymax	overall heat transfer coefficient 23.0 W/m2/K, outside temperature: 5.0 °c
	Xmax, Ymin	overall heat transfer coefficient 8.0 W/m2/K, outside temperature 20.0 °c
	Zmin	overall heat transfer coefficient 9.0 W/m2/K, outside temperature: 20.0 °c
	Zmax	overall heat transfer coefficient 35.0 W/m2/K, outside temperature 5.0 °c
Wall boundary condition		All surfaces: logarithmic law

An outdoor case (wind around a high-rise building) and an indoor case (a room heated by an air-conditioner in winter) were chosen deliberately: because first-year architecture students have not yet specialised—some will go on to design buildings, others to plan cities—these two classic themes introduce both the outdoor and indoor settings where airflow and heat shape the built environment.

In session 13, students chose their own analysis topic and set the simulation goals, model geometry and boundary conditions. This session enabled students to synthesise what they had learned in previous sessions and apply it to their own analysis topic. Further details on the instructional support and evaluation in this session are provided below in Sections 2.3 and 2.4.

The software *scSTREAM* (Cradle CFD 2023, Hexagon) was used, and the analysis environment was configured to enable access across the university campus. *scSTREAM* was selected because students could set up models, run calculations and view results through its graphical interface. It also provided the functions needed for airflow and heat-transfer analysis in buildings. These features suited an introductory course with limited time for learning software operation. Each student used a ThinkPad L380 laptop computer (Lenovo; Intel Core i3-8130U, 8 GB RAM, 128 GB SSD, Windows 10).

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2.3 MIDTERM AND FINAL REPORT ASSIGNMENTS

To ensure structured learning and assessment, students were required to submit both a midterm report and a final report as part of the CFD practical training. These tasks were designed to support students in planning, performing and reflecting on the analyses undertaken in session 13. Table 2 summarises the contents required for each report.

Table 2: Contents of the midterm and final reports.

NO.	CONTENT
Midterm report	
1	Overview of the analysis
2	Purpose of the analysis
3	Screenshots of the analysis model
4	Questions or clarifications about the analysis (reply by email)
5	Matters to discuss with the instructor (face-to-face consultation/advice) * If there are no specific matters to discuss, leave blank
Final report	
1	Overview of the analysis
2	Purpose of the analysis
3	Analysis conditions (size of analysis area, turbulence model, boundary conditions, *etc.*)
4	Screenshots of the analysis model and divided mesh
5	Images of the wind speed analysis results (planes of the *x*-, *y*- and *z*-axes)
6	Images of the temperature analysis results (planes of the *x*-, *y*- and *z*-axes) * Only if a temperature analysis was performed
7	Discussion of the results and impressions of the analysis
8	Questions or clarifications about the analysis

For the midterm report, students were asked to submit a brief overview of their planned analysis, its purpose, screenshots of the model and any questions or discussion points. In addition to the report, the analysis model and condition files (even at an intermediate stage) had to be submitted. This enabled the instructors to check whether each proposed analysis was feasible for an architecture novice, provide feedback and make adjustments if necessary. Questions submitted in the report or analysis data were answered via email or a cloud platform, and consultation sessions were arranged for students needing further support or showing high motivation.

For the final report, more comprehensive documentation was required, including specific analysis settings, visual outputs of the results and a discussion. Along with the report, students were required to submit the final model, conditions and result files. The final report was directly linked to the grading of the practical training. During the final session (session 14), instructors provided feedback by highlighting common mistakes—including incorrect boundary conditions, misalignment between model and domain, enclosed spaces within the analysis area, and unrealistic results due to unit setting errors—and explained how these issues could be resolved. Exemplary student work was also highlighted to encourage further learning.

Course assignments and reports, including those for the CFD practical training, accounted for 50% of the final grade. The final examination accounted for the remaining 50% and assessed lecture and practical training content through questions requiring written explanations and calculations.

2.4 INSTRUCTIONAL STRATEGIES TO ENHANCE CFD PRACTICAL TRAINING

Several instructional strategies were implemented to facilitate conceptual understanding (RQ1), increase engagement with environmental design (RQ2) and reduce barriers to learning (RQ3). The

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intended learning outcomes were to set up a simple CFD model, explain the boundary conditions, interpret the visualised results and reflect on the analysis. Students practiced these skills through guided exercises and a task in which they chose the analysis topic and conditions. The reports required in Table 2 recorded students' model settings, results and interpretations.

One instructor taught the course, with support from one graduate teaching assistant during lectures and four during practical sessions. During practical training, each instructor or teaching assistant supported about 22 students. Instructional materials incorporated relevant lecture content into the training documents. For example, mesh-generation procedures included discretisation concepts covered in session 6 in order to help students connect theory with practical applications.

In session 11, students were seated in order of their student ID numbers and divided into three groups in each row (Figure 2, left). Each group analysed a different high-rise building shape—standard rectangular, elongated along the *x*-axis and elongated along the *y*-axis—in order to grasp how geometry affects airflow patterns. In session 12, students were divided into two groups (Figure 2, right) and analysed a room with different numbers of glazed surfaces (one versus three) in order to examine the influence of thermal transmittance on indoor conditions. Peer comparison was encouraged at the end of each session in order to reinforce conceptual understanding and promote interactive learning.

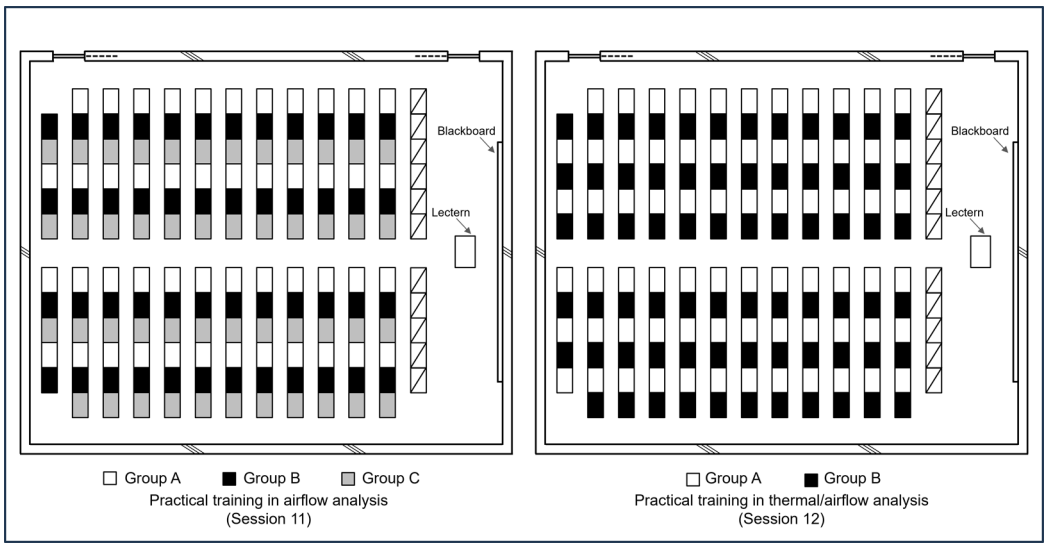


Figure 2: Grouping of students during the practical training sessions 11 (left) and 12 (right).

In session 13, students were encouraged to choose their own CFD analysis topic and conditions. Technical support and reference materials were provided to facilitate the analytical process. To ensure the accuracy and efficiency of the simulations, the following specific guidance was given. Students were advised to model in detail the areas that could significantly affect the results while simplifying regions with little influence; to maintain a proper balance of mass and heat fluxes throughout the system; and to carefully monitor the convergence status, revising boundary conditions or other parameters as needed and performing re-analysis in cases of divergence or persistent oscillations in the residuals. This task was intended to foster intellectual engagement (RQ2) and enable exploration of features that facilitate or hinder learning as students moved from guided exercises to analyses they planned themselves (RQ3).

3. MATERIALS AND METHODS

This section explains the strategy used to evaluate the course with respect to the three RQs. Each subsection highlights how the collected data relate to them.

3.1 OUTLINE OF THE ANALYSIS

Changes in understanding (RQ1), engagement and interest (RQ2) and perceived challenges and supports in the learning process (RQ3) were examined to evaluate the educational effects of

hybrid CFD instruction. Questionnaires were used to assess students' self-reported understanding, interest and difficulties during the course.

Because the CFD practical training was embedded in a required first-year course, random assignment to CFD versus no-CFD conditions was not adopted to avoid disadvantaging some students. Accordingly, this study uses a pragmatic course-evaluation design based primarily on students' self-reported understanding, interest and perceived difficulties; the findings are interpreted as changes in learning-related perceptions and barriers/facilitators rather than as causal estimates of CFD training effects.

Participation in the surveys was voluntary. Before responding, students were informed that their responses and examination results would be anonymised and used only to evaluate the educational effects of the course and report the findings. Only data from students who provided informed consent at the start of the survey were included in the analysis. Because the data are self-reported, they reflect students' perceptions; anonymous administration and the high response rate were intended to reduce social desirability and non-response bias.

3.2 ITEMS ASSESSED IN THE LECTURES

Self-assessment surveys were conducted after each lecture or practical session (sessions 1–13), during session 14 after completing the CFD practical training (post-CFD survey) and after the final examination (post-course survey).

The main survey items are summarised in Table 3, with the survey items and response formats provided in ***Table S1*** in the supplemental data online. The post-CFD survey, which was administered after the practical training was completed, gathered a wide range of data, including background characteristics (*e.g.* gender, academic experience), perceived changes in interest due to the CFD experience, and students' impressions of both the benefits and challenges of the practical training. Finally, the post-course survey asked students to retrospectively rate their level of understanding for each lecture at three distinct time points: (1) immediately after the lecture, (2) after completing the CFD practical training and (3) at the time of the final examination. Students indicated their understanding at each time point by placing a mark anywhere on a continuous 0–100 rating scale, including between tick marks. A score of 100 represented the highest level of understanding of the lecture content. Students also reported difficulties after each practical session (sessions 11–13). These session-specific items and the post-CFD survey items on difficulties and positive and negative aspects of the training allowed multiple selections from predefined options. The post-CFD survey included an 'other' option with a free-text field.

Table 3: Items assessed in the lectures.

Note: CFD = computational fluid dynamics; RQ = research question.

	SURVEY ITEM	TIMING OF DATA COLLECTION
Background variables (not directly related to the RQs)		
0-1	Gender	Post-CFD survey
0-2	Interest in the built environment field at the start of the course	Post-CFD survey
0-3	Difficulty with science and mathematics subjects	Post-CFD survey
0-4	Experience in considering thermal/airflow design at the start of the course	Post-CFD survey
0-5	Awareness of thermal/airflow design at the start of the course	Post-CFD survey
0-6	Prior knowledge of CFD analysis at the start of the course	Post-CFD survey
RQ1: Effects of hybrid CFD education on conceptual understanding		
1-1	Retrospective self-rating of understanding (continuous 0–100 rating scale) for each lecture at the three time points: (1) immediately after the lecture, (2) after completing the CFD practical training and (3) at the time of the final examination	Post-course survey

(Contd.)

SURVEY ITEM		TIMING OF DATA COLLECTION
RQ2: Effects of hybrid CFD education on intellectual curiosity and interest		
2-1	Self-assessed change in interest in each lecture's content after completing the CFD practical training	Post-CFD survey
2-2	Change in interest in the built environment field after completing the CFD practical training	Post-CFD survey
2-3	Change in awareness of thermal and airflow design considerations after completing the CFD practical training	Post-CFD survey
RQ3: Facilitators and barriers in practical CFD training for beginners		
3-1	Positive aspects of the CFD experience (*e.g.* intellectual satisfaction, visualisation benefits)	Post-CFD survey
3-2	Negative aspects of the CFD experience (*e.g.* lack of clarity, relevance or enjoyment)	Post-CFD survey
3-3	Reported difficulties during the CFD practical sessions (*e.g.* modelling, boundary setting)	After each practical session (sessions 11–13)

3.3 DATA ANALYSIS

In each analysis, students who were absent or did not complete the relevant survey or assignment were excluded. For the analysis of self-rated understanding, students who began studying for the final examination before the post-CFD survey were also excluded to reduce the influence of examination preparation. The Mann–Whitney *U*-test was used for comparisons between two groups, whereas for comparisons among three groups, the Kruskal–Wallis test was used, followed by pairwise comparisons using Dunn's test with Bonferroni adjustment.

4. RESULTS

4.1 RESPONDENT PROFILES

Both the post-CFD survey and the post-course survey were completed by 99 of the 112 participating students (response rate = 88%). Table 4 summarises the demographic characteristics and academic backgrounds of the respondents. The gender distribution was 61% male and 39% female, which closely reflects national trends among undergraduates in architecture-related programmes in Japan (Nagasawa *et al.* 2014). All students were first-year undergraduates enrolled in the Department of Architecture. Before the course, 95% of the students had no prior knowledge of CFD, and 90% had no experience with thermal or airflow design.

Table 4: Respondent profiles.
Note: CFD = computational fluid dynamics.

VARIABLE	CATEGORY	FREQUENCY (*N*)	%
Gender	Male	60	61%
	Female	39	39%
Grade	First year	99	100%
Faculty	Department of Architecture	99	100%
Prior knowledge of CFD analysis	Yes	4	4%
	No	70	71%
	Missing	25	25%
Experience in considering thermal and airflow (environmental) design	Yes	10	10%
	No	88	89%
	Missing	1	1%

(Contd.)

VARIABLE	CATEGORY	FREQUENCY (*N*)	%
Awareness of thermal and airflow (environmental) design considerations	High	5	5%
	Somewhat high	28	28%
	Neither	38	38%
	Somewhat low	21	21%
	Low	6	6%
	Missing	1	1%
Self-rated ability in science and mathematics	Good at	7	7%
	Slightly good at	36	36%
	Neither	36	36%
	Slightly not good at	11	11%
	Not good at	9	9%
	Missing	0	0%
Interest in the built environment field	High	6	6%
	Somewhat high	50	51%
	Neither	18	18%
	Somewhat low	18	18%
	Low	6	6%
	Missing	1	1%

In terms of awareness of thermal and airflow design, 34% of the respondents indicated a 'high' or 'somewhat high' level of awareness, and 27% indicated a 'low' or 'somewhat low' level. Regarding academic confidence, 43% rated themselves 'good at' or 'slightly good at' science and mathematics, while 20% reported difficulty in those subjects. Interest in the built environment field was generally strong, with 57% indicating 'high' or 'somewhat high' interest, compared with 24% who reported low interest.

4.2 EFFECTS OF HYBRID CFD EDUCATION ON CONCEPTUAL UNDERSTANDING (RQ1)

Figure 3 presents students' self-rated understanding of each lecture session at three points in time from the post-course survey (for the pre-CFD survey results, see also ***Figure S1*** in the supplemental data online): (1) a retrospective rating of their understanding immediately after the lecture, (2) a retrospective rating of their understanding after completing the CFD practical training and (3) their understanding at the time of the final examination.

Substantial increases in self-rated understanding were observed between points 1 and 2, particularly in session 10 (from 54.9 to 68.2) and session 7 (from 45.4 to 60.1)—the topics most directly reinforced by the CFD practical training. Meanwhile, session 5 showed a pronounced gain between points 2 and 3 (from 44.2 to 68.1), which might reflect additional learning resulting from test preparation or delayed comprehension.

The results of the Kruskal–Wallis and Dunn tests revealed statistically significant differences in self-rated understanding across the three time points in several lecture sessions (*e.g.* sessions 7 and 10 between points 1 and 2; $p < 0.01$). These findings indicate that students retrospectively perceived their understanding to have increased, particularly for abstract or complex topics.

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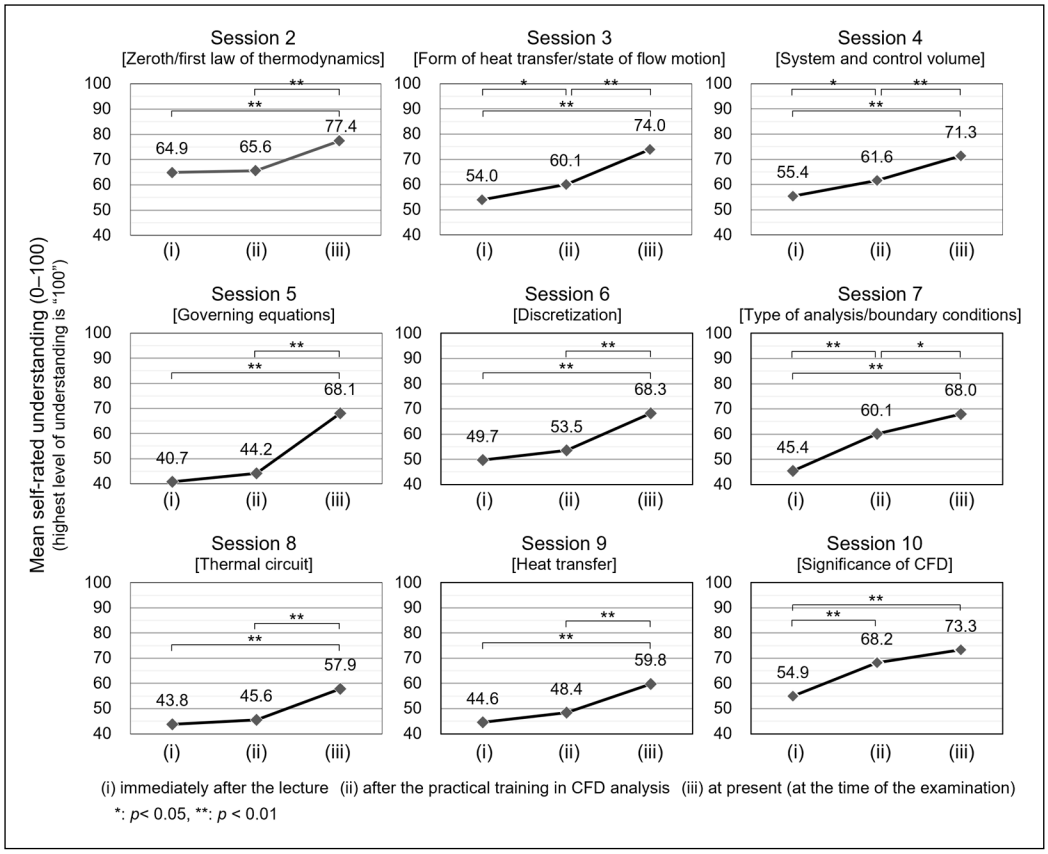


Figure 3: Changes in students' understanding of each lecture content at three time points: (1) immediately after the lecture, (2) after computational fluid dynamics (CFD) practical training and (3) at the final examination.

4.3 EFFECTS OF HYBRID CFD EDUCATION ON INTELLECTUAL CURIOSITY AND INTEREST (RQ2)

Figure 4 shows the self-reported changes in students' interest in each lecture's content after the CFD analysis experience. Excluding session 1 (guidance), the level of interest increased substantially across most sessions. For all sessions, more than 40% of students answered 'increased' or 'somewhat increased', with several lecture sessions exceeding 80%. The lectures that showed the largest gains in interest were session 10 (significance and overview of CFD) and session 7 (types of analysis and boundary conditions). Negative responses (*i.e.* 'decreased' or 'somewhat decreased') were rare, remaining less than 5% in most sessions.

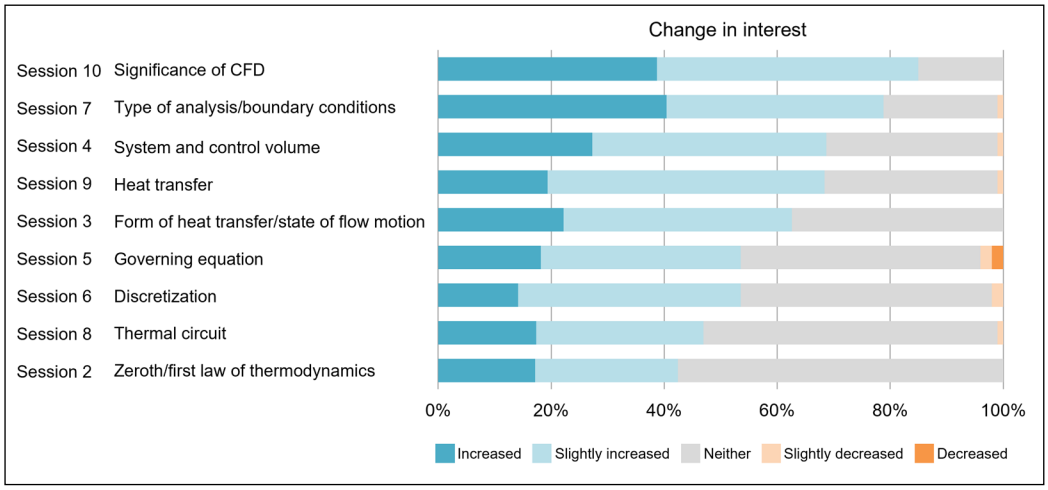


Figure 4: Changes in students' interest in each lecture content following computational fluid dynamics (CFD) analysis.

Figure 5 shows students' self-reported changes in interest in the field of the built environment and awareness of thermal and airflow design considerations after completing the CFD analysis. More

than 90% of the respondents indicated increased or somewhat increased awareness and interest, suggesting that the hands-on training had helped deepen their engagement with environment-conscious building design.

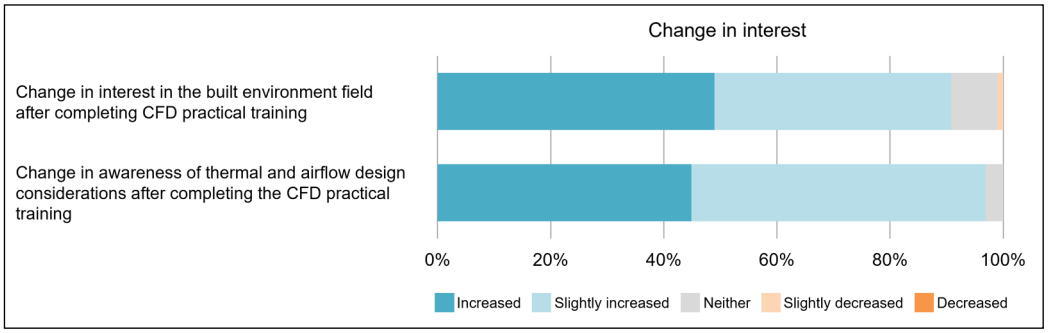


Figure 5: Change in students' interest in built environment and thermal/airflow design after computational fluid dynamics (CFD) practical training.

4.4 FACILITATORS AND BARRIERS IN PRACTICAL CFD TRAINING FOR BEGINNERS (RQ3)

Figure 6 presents the reported difficulties encountered during the CFD training, namely, sessions 11 (airflow analysis), 12 (thermal-airflow analysis) and 13 (applied analysis). The most frequently reported difficulty in session 11 was the operation and handling of the analysis software (28 responses), followed by setting up the analysis contents (13 responses). In session 12, the types of difficulties were more varied, with boundary condition-setting (10 responses) and visualising the results (eight responses) emerging as major issues. By session 13, difficulties were more evenly distributed across categories, with boundary condition setting (12 responses) and visualisation (11 responses) reported most often, followed by modelling (six responses) and setting up the analysis contents (seven responses). These findings suggest that students initially struggled primarily with software operation, but as the training progressed to more advanced and applied analyses, challenges shifted toward technical aspects of model construction, boundary condition setting and result interpretation.

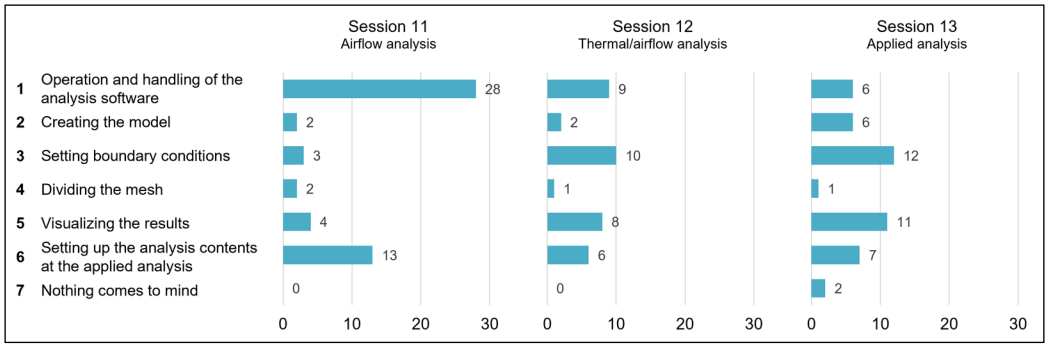


Figure 6: Reported difficulties in computational fluid dynamics (CFD) practical training: comparison across sessions 11–13.

Figure 7 summarises students' evaluations of the CFD analysis experience. The most common positive response was that performing the CFD analysis itself was a valuable experience (85 responses), followed by satisfying one's intellectual curiosity (61 responses). Many students also felt that the activity broadened their perspective on architectural studies, and 45 students (46%) expressed an interest in using CFD in future architectural design projects. In contrast, the most frequent negative response was 'nothing comes to mind' (47 responses). A total of 19 students selected the option indicating that there were insufficient analysis examples to help them understand the content covered in the lectures. Overall, the positive responses substantially outweighed the negative ones.

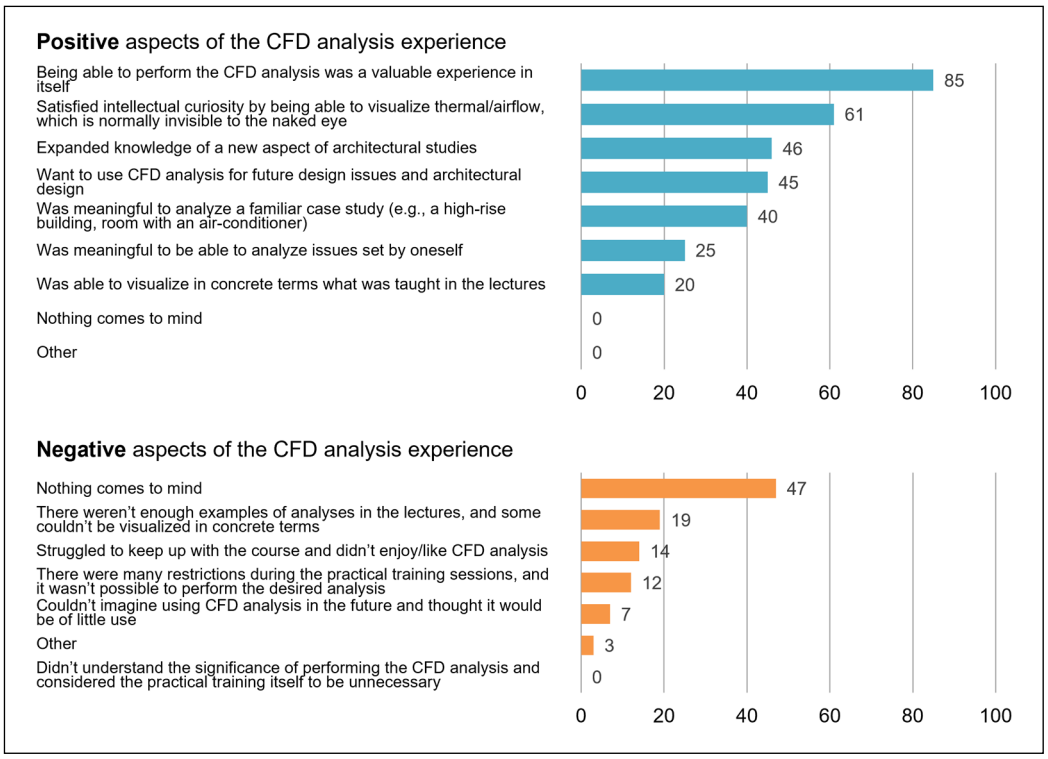


Figure 7: Reported positive and negative aspects of the computational fluid dynamics (CFD) practical training.

5. DISCUSSION

5.1 EDUCATIONAL EFFECTS OF HYBRID CFD TRAINING

This study designed, implemented and evaluated a hybrid course combining lectures on thermo-fluid dynamics with hands-on CFD practical training for first-year architecture students. Three main findings align with the three RQs.

First, students' self-rated understanding increased over the course (RQ1). Self-rated understanding rose after the CFD sessions compared with immediately after the lectures, with the largest gains in topics directly reinforced by the training (*e.g.* boundary conditions and the overview/significance of CFD). Non-parametric tests indicated significant differences across the three time points in several lecture sessions ($p < 0.05$). The pattern supports an association between the training and improved perceived understanding. This trend is similar to that observed in previous studies (Adair *et al.* 2014; Beausoleil-Morrison & Hopfe 2015; Jaeger & Adair 2010, 2012; Keller *et al.* 2007), which reported that the use of simulation improves understanding and learning effectiveness. The course design strategy likely contributed to these gains, including staged tasks (airflow → thermal airflow → applied); linking lecture concepts to the training workflow; and end-of-session peer comparisons, which made abstract content more concrete through visualisation, helping to mitigate 'black-box' use of software defaults.

These patterns also indicate how the hybrid format compares with the conventional lecture-only approach to teaching thermo-fluid dynamics. In a lecture-only model, abstract concepts such as boundary conditions or turbulence remain difficult to visualise and tend to be engaged with passively. Here, self-rated understanding of several topics rose specifically after the hands-on sessions rather than after the lectures alone, suggesting that running and interpreting simulations helped students connect physical principles to building contexts in a way that lectures by themselves did not. For beginners, the core difficulty lies as much in grasping the underlying fluid mechanics as in operating the software and visualising the physics appears to support the former.

Second, the course increased intellectual curiosity and interest in environmental design (RQ2). Most students reported greater interest in the lecture topics after the hands-on CFD practical training experience, and more than 90% reported higher interest in the built environment field and awareness of thermal/airflow design considerations. Many also expressed their intent to apply CFD

in future architectural design projects. These results are consistent with prior reports in engineering education showing pre/post-improvements when CFD is integrated into curricula (*e.g.* Adair *et al.* 2014; Aung 2003; Berg *et al.* 1999; Hu *et al.* 2008; Spall & Hailey 2000). The introductory course is intended to help students understand thermo-fluid phenomena and interpret CFD results when evaluating airflow and thermal conditions in later design studios and graduation design projects.

Third, the study identified concrete facilitators and barriers in beginner-level CFD work (RQ3). Reported difficulties varied by training stage: software operation and handling dominated in the early practical training session, whereas boundary condition setting, visualising results and model creation were more prominent in later sessions. The instructional structure addressed these challenges in three ways. (1) A midterm checkpoint required submission of partial models and analysis files; instructors and teaching assistants responded to written questions and met with students as needed, which helped correct feasibility issues at an early stage. (2) Training documents incorporated lecture content at anticipated trouble spots (*e.g.* discretisation in mesh set-up), thereby reducing reliance on default software presets and supporting deeper understanding. (3) The final session (session 14) provided whole-class feedback reviewing frequent error patterns identified in the final reports (*e.g.* mismatched domains, enclosed volumes, unit mistakes) and demonstrated correct remedies alongside exemplary submissions. Open-ended student comments requesting clearer guidance on diagnosing failed runs reinforced the value of this feedback loop. In addition, exemplary student work was highlighted during the final session and is presented in ***Figure S2*** in the supplemental data online. These cases demonstrated appropriate boundary condition settings, effective meshing strategies and the clear interpretation of results, providing concrete references for other students and further illustrating the potential learning outcomes of the hybrid CFD course.

Building on these observations, the importance of error literacy in CFD education should be emphasised. Because CFD entails modelling, discretisation and convergence errors, students must learn to assess whether results are reasonable and then verify them accordingly (SHASE 2017). Benchmark problems (Aalborg University n.d.; Ito *et al.* 2015a, 2015b, 2015c, 2015d) and simulations of measured environments are effective vehicles for evaluating this skill, and prior BPS education studies have shown that benchmark tasks prompt critical evaluation of simulation output (Beausoleil-Morrison & Hopfe 2015, 2016). In the present course, convergence monitoring and boundary-condition checks were required deliverables; extending this with structured benchmark assignments and selected references to established CFD guidelines (AIJ 2020; Ito *et al.* 2015a) might further strengthen students' ability to validate their work.

Taken together, the evidence presented in this paper indicates that a tightly aligned hybrid model—lectures that foreground core principles, training that visualises those principles on targeted tasks, early checkpoints with responsive support from instructors and teaching assistants, and clear, example-driven feedback—was associated with higher self-rated understanding and reported interest among first-year students while revealing where additional support is needed most. The course elements can be practically implemented in regular coursework (assistant support, peer comparison, staged complexity) and are potentially adaptable to architecture programmes that aim to integrate CFD without overloading students at the introductory level.

5.2 STUDY LIMITATIONS AND FUTURE CHALLENGES

This study quantified the educational effects of incorporating CFD analysis into a course; however, stronger evidence would require more robust designs, including randomised controlled trials. However, such a trial comparing groups with and without CFD training was not feasible, given the need to maintain fairness in an actual course setting. Because the order of response options was not changed, it may have influenced students' choices. Consistent with the introductory aim of the course, the CFD settings were intentionally simplified, and formal validation or mesh-independence testing was not included. These topics should be incorporated in later specialised courses, laboratory study or advanced follow-up work. Another limitation was the lack of emphasis on self-verification of results. Students should be encouraged to perform benchmark tests or simulations of measured environments to understand potential sources of error. Providing motivated students

with guidance on studying CFD after the course might further enhance the benefits of CFD training. Finally, it remains unclear whether CFD analysis directly influenced students' design proposals. Follow-up surveys should be conducted to evaluate how exposure to CFD shapes students' future architectural designs.

6. CONCLUSIONS

This study implemented and evaluated a hybrid course integrating lectures on thermo-fluid dynamics with practical computational fluid dynamics (CFD) training for first-year architecture students. The course was designed not only to introduce fundamental physical concepts but also to help students begin to recognise that simulation results require checking and interpretation. By incorporating CFD training within a broader physics curriculum, the course demonstrated how abstract theoretical knowledge can be connected to practical, design-relevant applications.

Students reported increased understanding of lecture content, increased interest in the built environment, and a greater awareness of thermal and airflow design considerations after the CFD training. A total of 45 students (46%) also expressed interest in using CFD in future architectural design projects. The course asked students to check convergence, review boundary conditions and consider whether the results were reasonable. This was intended to help students judge the reliability of CFD results. This emphasis on evaluating the reliability of results is particularly relevant in architectural education, where simulation is often adopted without sufficiently careful evaluation. Lectures, demonstrations and supervised practice were combined to help first-year students learn basic CFD procedures.

Although the present study focused on short-term learning outcomes, the long-term impact remains to be clarified. Ascertaining whether students continue to apply CFD in later studio projects or professional practice will require further follow-up through longitudinal surveys or portfolio analyses. Moreover, the inclusion of structured benchmark assignments and curated references to established CFD guidelines might further enhance students' capacity to validate their work.

In summary, the present course design offers a practical model for introducing CFD to architecture students at an early stage. The integration of theory, practice and reflection appeared to support learning while also highlighting areas where instructional strategies might be refined. The experience contributes to a broader discussion on how simulation-based methods can be meaningfully incorporated in architectural education.

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AI DECLARATION

The authors used ChatGPT (OpenAI) and Claude (Anthropic) to assist with drafting and editing text. They reviewed and revised the output and take full responsibility for the content of the manuscript.

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COMPETING INTERESTS

The authors have no competing interests to declare. S.K. is a member of the journal's editorial board, but had no involvement in the review processes and editorial decisions for this paper.

DATA ACCESSIBILITY

The data supporting the findings of this study are not publicly available because they contain potentially identifying information about individual students; anonymised, aggregated data are available from the corresponding author on reasonable request, subject to institutional approval.

ETHICAL APPROVAL

Institutional approval was not required. Participation in this study was voluntary and with informed consent. Students could choose not to respond. They were informed that their responses and examination results would be anonymised and used only to evaluate the educational effects of the course and report the findings. Only data from students who provided informed consent were analysed.

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SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: https://doi.org/10.5334/bc.889.s1

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