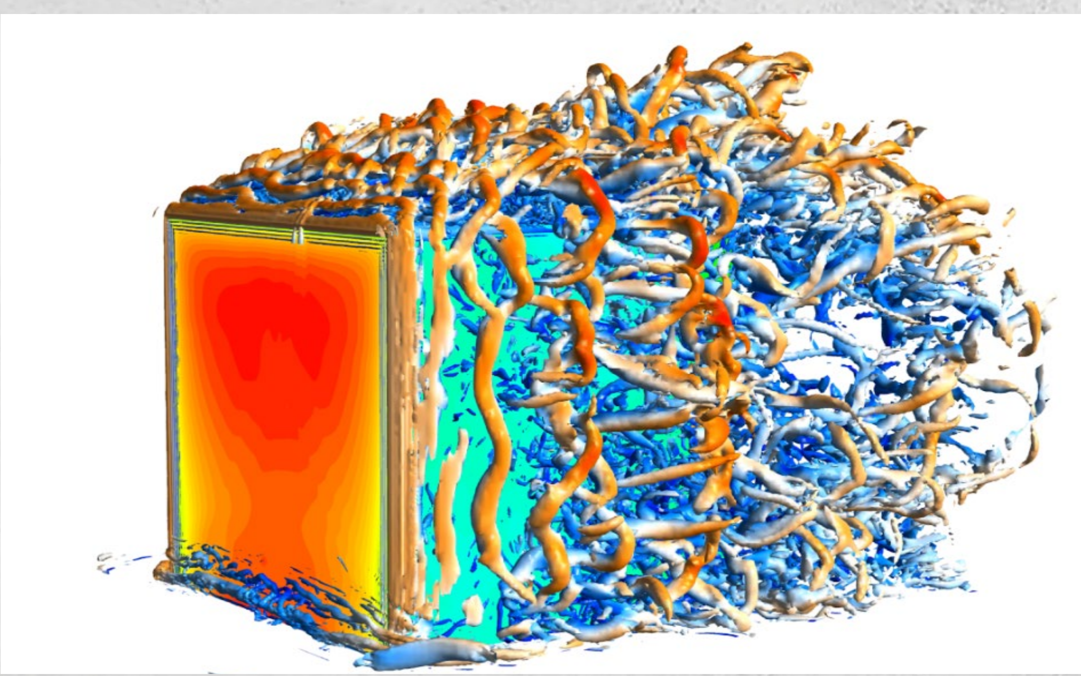
Project #57: Wind Comfort Simulation and a New Engineering Design Process

FINAL REPORT



CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

CFD	computational fluid dynamics
D&T Building	Design and Technology Building
HVAC	heating, ventilation and air conditioning
IDDES	improved delayed detached-eddy simulation
RANS	Reynolds averaged Napier-Stokes
SST	shear stress transport
URANS	unsteady Reynolds-averaged Napier Stokes

CONFIDENTIAL:	☐ Yes ☒ No
Author/s of this report:	David Burton, Daniel Tudball Smith, Mark Thompson
Date of this report:	November 2024
Project completion date:	15 December 2023
Program Leader reviewer:	
Project title:	B4.0 CRC #57: Wind Comfort Simulation and New Engineering Design Process
Project duration:	1 years, 7 months
Partners:	1. Lendlease Digital Australia 2. Monash University 3. Building 4.0 CRC Limited
Project team members:	1. DAVID BURTON 2. DANIEL TUDBALL SMITH 3. MARK THOMPSON 4. SHIBO WANG 5. TIM BUTLER 6. MARTIN FOWLER
Acknowledgements:	We thank Tim Butler for his input and support, and, also, Martin Fowler for his input particularly in the later stages of the project. We would also like to acknowledge those that were involved in the idea and definition of the original project scope, including Karl-Heinz Weiss, Jesse Hallen, Steven Huang and Shahram Houreh. Thanks also to Harry Scott for his assistance with the experimental data acquisition. Finally, we would also acknowledge the Building 4.0 CRC for providing the financial support and administrative support to enable this project to proceed.

Disclaimer

The Building 4.0 CRC has endeavoured to ensure that all information in this publication is correct. It makes no warranty with regard to the accuracy of the information provided and will not be liable if the information is inaccurate, incomplete or out of date nor be liable for any direct or indirect damages arising from its use. The contents of this publication should not be used as a substitute for seeking independent professional advice.

1. EXECUTIVE SUMMARY

This project investigated methodologies for assessing and evaluating the wind comfort aspect of building design, using these insights to identify opportunities for enhancing the current linear approach to building design. The study suggests that design processes can be made more efficient, especially in the early stages, by using feedback from basic computer simulations, rather than waiting for input from more detailed and advanced studies later on. The study highlights the importance of adding checks after construction, whenever possible, to continuously verify and validate simulation methods. This is key for retaining knowledge and improving processes in future projects.

To fulfil the project objectives, a combined experimental and computational fluid dynamics (CFD) simulation program was devised. The experiments formed the reference case for verification and comparison to help evaluate and refine the CFD methodology. To achieve this, a series of wind tunnel tests were conducted at Monash University using scale building models. The focus was on fine-tuning and optimising the CFD methodology for two building geometries: the Silsoe cube, a low-rise experimental building, and the Design and Technology Building (D & T Building), a medium-rise structure at Monash University.

Figure 1. Design and Technology Building Monash University.

The study found that trends in both cladding pressures and pedestrian winds were in good agreement, especially after optimisation of the process. Nevertheless, some discrepancies in magnitudes were observed. These minor discrepancies require further investigation, but the results build confidence that the carefully verified CFD processes can reliably simulate the important flow characteristics that lead to high pedestrian wind speeds. In contrast, relying on models and processes that are not verified carries a significant risk of obtaining misleading results. A key deliverable from this part of the project was the development of an efficient approach for conducting wind comfort simulations on medium-rise buildings, which was recommended to the industry partner.

The CFD model was then used to systematically study wind and pressure predictions of different computational models, focusing on the impact on accuracy and computational cost. Broadly, these models explored (i) the presence of surrounding geometries around the target building, (ii) geometric fidelity of the models, (iii) uniformity of climate winds, and (iv) the number of wind directions considered in the assessment. This gave rise to a series of technical recommendations as to the computational approach based on the stage of the project, considering the information that was likely to be available. This approach addressed the issue that wind studies are often conducted relatively late in the design process, when detailed geometry is available, serving primarily as sign-off tests. Unfortunately, this timing restricts the ability to make design changes or identify issues early, leading to costly adjustments, delays, and design reworks. A key finding is that valuable data can be obtained much earlier in the design process using simplified models, wind climate estimates, and low-resolution building designs. This early-stage analysis can alert designers to potential major issues, such as whether wind comfort is likely to exceed allowable criteria, enabling early design intervention, reducing costs, and ultimately delivering a better product.

This study generated several recommendations for further research. Firstly, while the project successfully created feedback within the design stages between wind tunnel testing and CFD approaches, it is important to extend this feedback loop to include the operational stage of a structure. This could be achieved by instrumenting buildings or examining already instrumented buildings to compare design predictions with actual performance. A significant issue in wind comfort design is the difficult and, consequently, lack of as-built measurements. Conducting such investigations presents an opportunity to extend this work, focusing on wind comfort or similar design attributes. This information could provide a competitive advantage by offering insights into the as-built form, effectively closing the loop between design and operation. The D & T building, for example, has much of this information for other attributes, though it unfortunately lacks sensors for wind loading or comfort.

Secondly, this study should be extended to other geometries. The D&T Building was selected; however, the findings may not be universally applicable to different structure geometries. For example, results obtained from this building might not be consistent with those for a high-rise building (e.g., 150+ meters tall). The D&T Building is approximately 20 meters tall, and it is reasonable to assume that its aerodynamics are primarily influenced by the wind environment close to the ground. In contrast, a high-rise building extends further into the atmospheric boundary layer, where downwash from higher elevations with greater wind momentum significantly impacts pedestrian-level winds.

While the primary focus of this work was on the technical application of wind comfort simulation techniques, the overarching goal was to use this attribute as a pilot to determine whether similar approaches could be applied to other design attributes. This leads to a third recommendation: to expand the scope of this study beyond the ‘standard’ wind study, which concentrated on CFD and wind tunnel studies aimed at predicting wind speeds, wind loads, and pressures. The impact of the study can be significantly enhanced by extending feedback approaches through digital modelling into other areas such as HVAC design, ventilation, fire safety, lighting, and connectivity. Such a broader application will significantly enhance building outcomes by enabling a more comprehensive understanding and optimisation of building performance across multiple attributes. This holistic approach presents a real opportunity to create a meaningful impact on the building design process.

2. PROJECT OVERVIEW

This project aims to highlight opportunities to improve the current building design process. The approach for integrating technical processes into the design and improvement of medium-rise buildings is evaluated in the context of the wind comfort performance attribute. The intention is for the findings to guide future design process improvements, beyond the wind comfort attribute, by transforming the typical linear process into one that incorporates feedback loops. Specifically, data from later stages can be used to evaluate and calibrate earlier stages, enhancing the knowledge base and thereby improving future methods by bringing design input forward to achieve better outcomes.

Project Background and Motivation

The expectations for new buildings are increasing, with aims to enhance productivity, performance, and sustainability, ensuring that these structures exceed modern standards for efficiency, liveability, environmental responsibility, and occupant enjoyment. There are many design attributes that affect the building's overall performance and perceived performance. Wind engineering and comfort, structural dynamics, thermal systems (HVAC), acoustics, fire safety, lighting design, and energy efficiency are all examples that require specialised technical input.

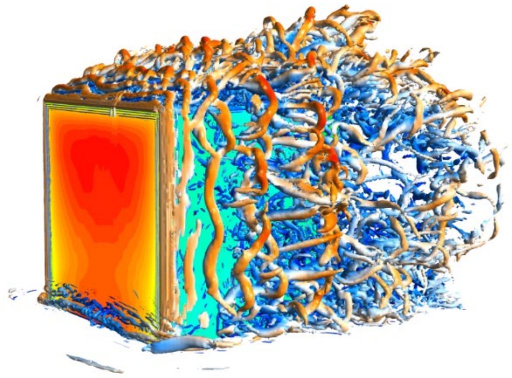


Figure 2. Flow over cubic building, unsteady CFD (IDDES).

The design and analysis of these building performance attributes can be highly technical, often requiring engagement or collaboration with consultants and the use of complex computer simulations. However, in a linear design process these studies can be specific, point-in-time tasks, frequently treated as a check-box exercise, allowing for little to no revisiting of earlier decisions. In some cases, consultants, or in-house experts, are brought into the project merely to assess compliance or performance and to suggest improvements, with limited opportunities to consider the broader performance context. This approach can result in missed opportunities for efficient integration into the project, early issue identification, and, importantly, evaluating the accuracy of methodologies (such as simulations) against the final as-built condition. Consequently, when the asset is eventually handed over for ongoing operation, the business retains limited design knowledge and materials.

This drives the primary motivation for this project: to explore the opportunity to implement an iterative, feedback-driven design process where design decisions are continuously evaluated and refined based on feedback, allowing for adjustments and improvements throughout the project's development.

These issues, naturally, can be present in various aspects of building design. In this project, we adopted the process of assessing pedestrian-level winds using CFD as a pilot case to explore opportunities for improving the design process. Consequently, the primary intellectual and academic focus, occupying the majority of the project's time and emphasis, was dedicated to studying and optimising simulation techniques and developing recommendations for their implementation in the wind comfort simulation and evaluation process.

Wind Comfort & Simulations

Wind comfort refers to the assessment and management of wind conditions around and within buildings to ensure safety, liveability, and overall user comfort. From a building design perspective, wind comfort involves evaluating how wind interacts with the built environment, particularly at pedestrian levels. The presence of buildings modifies the wind environment in their vicinity, with design factors such as shape, orientation, and height, as well as features like canopies, balconies, and landscaping, all contributing to how wind is channelled or disrupted around the structure. Importantly, the wind environment is also influenced by location-specific factors, including the wind climate, surrounding terrain, topography, and nearby structures.

The impact of a building's wind comfort design is typically evaluated during the planning approval process, but the true effect is often only realised in the as-built state. The success or failure of wind comfort design may not be obvious, but it ultimately can be observed in how the building and its surrounding spaces are utilised. Poor wind comfort outcomes can lead to underutilised spaces, where areas intended for outdoor dining, cafes, or gathering are avoided due to discomfort, thereby diminishing the vibrancy and economic potential of the space.

Pedestrian-level winds are analysed using either (or both) a computer model through CFD or a scale model wind tunnel test. However, by the time these analyses are performed, the ability to make substantial design changes to mitigate negative wind effects is often limited, reducing the opportunity to address potential issues effectively. Available countermeasures involve costly and time-consuming redesigns or retrofitting, such as adding wind barriers, or altering the surrounding landscape. These changes not only increase project costs but can also lead to delays and disrupt the overall project timeline. This presents an opportunity to explore how wind comfort information can be obtained earlier in the design process, allowing for more effective and less disruptive solutions.

There are significant technical challenges in predicting wind flows around buildings, which are now commonly evaluated using CFD. One major challenge is the substantial computational resources required, particularly for complex urban environments that demand high-resolution meshes (meaning lots of calculations). The level of detail needed to accurately capture airflow patterns around intricate architectural features adds further complexity to the process. Additionally, limitations in turbulence modelling make it difficult to accurately represent the turbulent and chaotic nature of wind, necessitating the use of simplified models that may not capture all relevant wind phenomena. The need to perform simulations for multiple wind directions (yaw angles) and account for specific terrain conditions further increases the number of required simulations, increasing the computational load. Moreover, setting up the geometry and creating the mesh, by discretising the domain into smaller elements, is a complex and time-consuming process that demands specialised expertise and careful attention to ensure accuracy.

Together, these challenges lead to simplifications in the approach to enhance overall efficiency; however, with limited standardised methods, these can result in inaccurate outcomes if not carefully correlated. In other words, while obtaining CFD results is relatively easy, achieving outcomes that are both efficient and reliable is difficult. Without checks in the as-built configuration, these errors may go unnoticed and uncorrected. Therefore, an opportunity arises to evaluate current CFD approaches, thereby enhancing the correlation with the as-built result or outcome.

Project Aims and Objectives

The project objectives were refined through the early stages of the project. There were three main objectives, however achieving the first became the core focus of this project, due to the scope change described below. The objectives are summarised below.

Objective 1. The current CFD (Computational Fluid Dynamics) process for wind comfort / loading design capability within the partner's business will be a pilot case for altering the linear process with a feedback loop, with the first objective to benchmark the current CFD studies and calibrate the results with lab data (i.e. wind tunnel testing results).

Objective 2. Identify opportunities for a feedback loop pathway to link the operational data back into the design process and outline an Autonomous Engineering Design Roadmap.

Objective 3. Explore applications to other engineering design disciplines including but not limited to fire, water, thermal, occupancy, lighting, electricity, and connectivity.

Project Scope Change

During the first quarter of the project, the industry partner (Lendlease) underwent a restructuring that reduced their ability to support the original project scope. This restructuring also led to changes in the practical implementation of a digital feedback loop strategy, following the redirection of their digital business. As a result, the project scope was adjusted and abridged. Without a dedicated in-house simulation team, the potential feedback flow became complicated by contractual and domain knowledge barriers within the client/design team relationships. Consequently, the key aim of this project shifted to applying and optimising CFD simulation techniques for the efficient prediction of pressures and pedestrian-level wind speeds on the selected built structure. This refocusing meant the project concentrated on *Objective 1*.

Project Deliverables

The key project deliverables and comments in relation to the achievement of each deliverable are provided in this section.

1. **Set-Up and Optimisation of CFD Simulations:**

   Set up, optimise, and perform CFD simulations on a low-rise building and an as-built structure.

2. **Design and Manufacture of Wind Tunnel Experimental Set-Up:**

   Design and manufacture an experimental wind tunnel set-up for the two geometries and conduct wind tunnel tests using Irwin probe sensors and hot-wire anemometry.

3. **Correlation and Synthesis of Results:**

   Synthesise CFD and wind tunnel results to correlate and establish a reference CFD simulation set-up.

4. **Evaluation of CFD Approaches:**

   Evaluate the performance of various CFD approaches for predicting wind environments.

5. **Consideration of Wind Tunnel Testing Limitations:**

   Assess and document the limitations of wind tunnel testing in the context of the study.

6. **Technical Report:**

   Deliver a technical report to the industry partner, detailing the methodology and approach used in the simulations (not included in this report).

7. **Development of Feedback Loop Recommendations:**

   Develop recommendations for incorporating feedback loops into the design process.

Project Approach

We first selected two buildings, one low-rise and one medium-rise, to serve as the subjects of the study. Both buildings were evaluated using CFD and wind tunnel testing, described further below. Experiments were undertaken in the Monash closed-jet wind tunnel, and CFD simulations were performed using high-fidelity, computationally intensive models to obtain the detailed and accurate data needed for validation through comparison with the wind tunnel tests. The CFD simulations were conducted using a combination of high-performance computing infrastructure at Monash, obtained through the project, as well as resources from the National Computational Infrastructure.

The low-rise building adopted is a reference geometry for which some existing field data is available (the “Silsoe Cube” as described in Richards, et al. (2007)) and the medium-rise building is an existing built structure. A number of medium-rise buildings were considered and after consultation with the industry partner the Design and Technology Building (the D&T Building) located at Monash University, Clayton campus in Victoria, was selected. As a Monash building we had access to the building geometry (CAD) files and there are future opportunities for more detailed data collection, further the industry partner was involved in the build. The D&T Building is shown in Figure 3, along with one of the wind tunnel the models of the Silsoe cube equipped for pressure measurements.

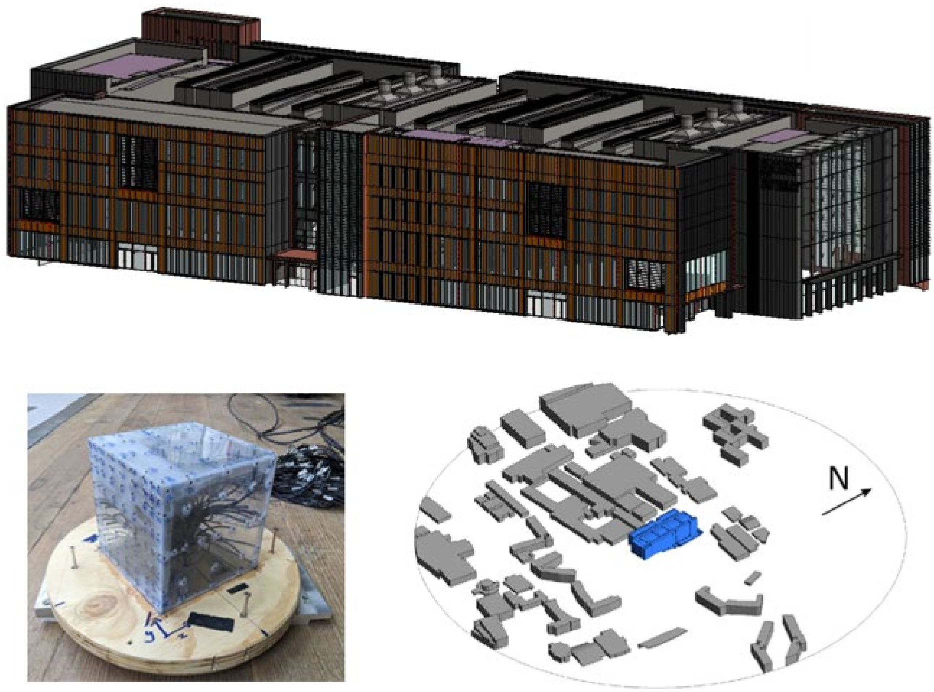


Figure 3. CAD geometry of D & T Building (top); pressure-tapped Silsoe Cube wind tunnel model (lower left); and D&T Building and Surroundings geometry for CFD study (lower right).

Experimental data was obtained from scale models of the Silsoe cube (1:40 scale) and D & T Building (1:400 scale). The Silsoe cube has a full-scale height of approximately 6 metres in full-scale and the D & T Building dimensions are 22 × 47 × 112 m^3 (height × width × length). For both models, data was obtained using a combination of instruments: dynamic surface pressure measurements via pressure tapping, hot-film anemometers, and Irwin probes (Figure 4).

The Silsoe Cube is located in a field with limited nearby flow obstructions, it was tested in a low turbulence boundary layer and a simulated atmospheric boundary layer. Whereas the winds over the D&T building are strongly affected by the surrounding buildings. Nevertheless, simulations and wind tunnel studies were performed for the D&T building both in its true context (i.e., with surrounding buildings) and a case without surround obstructions (i.e., in isolation). This provided three main datasets for benchmarking and calibrating the CFD models: the Silsoe cube, D &T Building (isolated) and D& T Building (surrounds).

Two sets of CFD simulations were undertaken. Initially, the first set aimed to establish a benchmark approach within the software by refining techniques for boundary layer modelling, meshing, and turbulence modelling. This also served to evaluate the relative performance of these approaches. For example, the use of turbulence models such as K-epsilon, K-omega, and SST, along with the computational approaches of RANS, URANS, and IDDES, were compared. Second, an approach was taken to investigate the sensitivity of the model's results to various parameters. In particular, the effects of significantly lowering mesh resolution, reducing the number of buildings simulated in proximity to the D & T Building, reducing the number of yaw angles simulated and decreasing the resolution of the provided geometry were examined. These efforts aimed to determine how representative the lower-resolution results are and assess the potential value of conducting simulations with the type of data that might be available early in the design process.

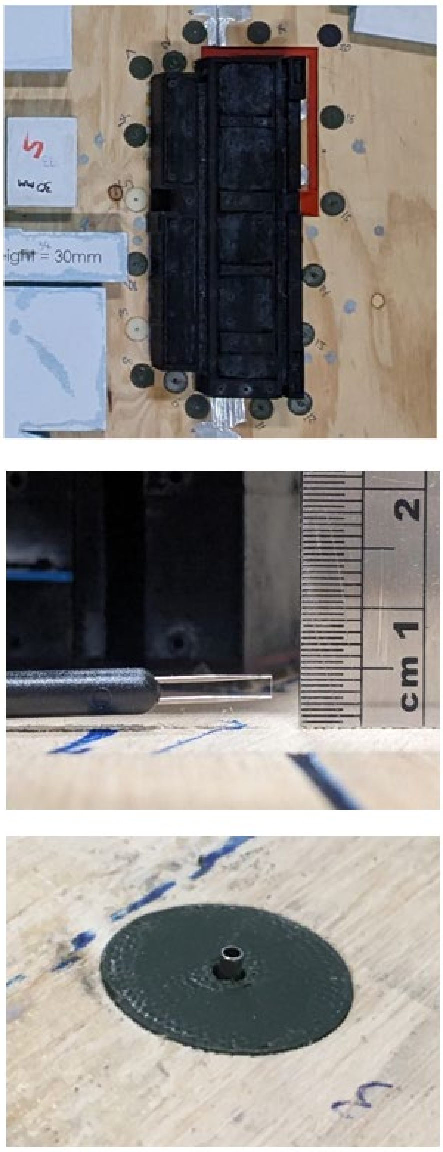


Figure 4. Wind Tunnel Model of D & T Building viewed from above, showing location of Irwin probes installed in the vicinity of the building (top); hot-film anemometer (centre); close-up image of Irwin probe.

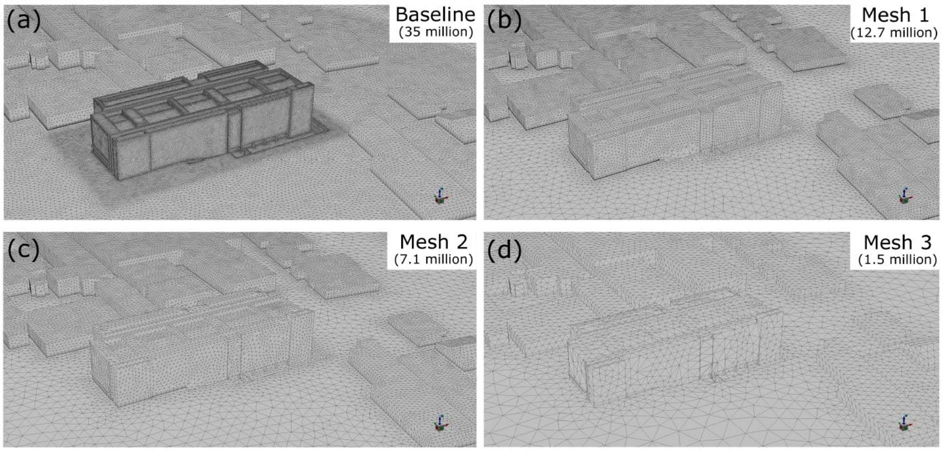


Figure 5. Images of surface mesh for different resolution cases investigated (a) 35 million cells; (b) 12.7 million cells; (c) 7.1 million; and (d) 1.5 million.

3. PROJECT FINDINGS & OUTCOMES

The key technical findings have been delivered in a technical report to the industry partner, addressing Objective 1. The main findings of this report focus on the pilot study and the insights it provides into the opportunity for the implementation of a feedback loop into future design process for building performance (Objective 2 & 3).

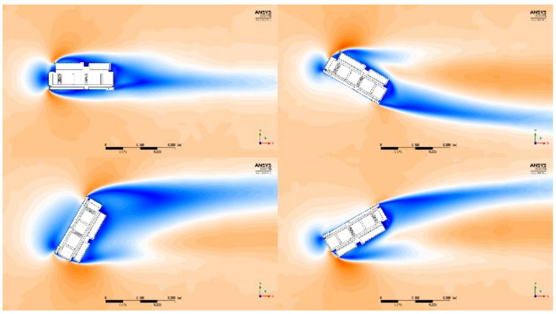


Figure 6. Flow velocity at pedestrian height for the isolated D & T Building for different wind directions (wind direction is left to right).

Project Findings

The following provides a generalised discussion of the findings from this work. More detailed technical findings have been delivered that consider the approach to wind comfort studies using different computer simulation techniques and the use of different experimental measurements for their validation. These studies aimed to identify an opportunity to improve the design process. The generalised technical findings and their implication are:

1. A technique for simulating pedestrian level winds of medium-rise buildings was developed that balanced computational cost, model complexity and accuracy. The evaluation of this RANS model accounted for mesh-resolution, turbulence modelling, model detail, detail of surroundings, simulations time and boundary conditions. Unfortunately, due to the change in scope discussed above, Lattice-Boltzmann methods could not be included in this study. Despite this, the process of developing this technique identified that inappropriate model set-up can lead to misleading results. It is therefore vital that any CFD methodology is calibrated against experimental data.

   For example, Figure 7, highlights the sensitivity of the simulations to different mesh set-ups near the corner of a building, observed as a change in the predicted wind speeds. This reinforces that designers must prioritise the proper validation of their models to ensure accuracy and reliability in the design process.

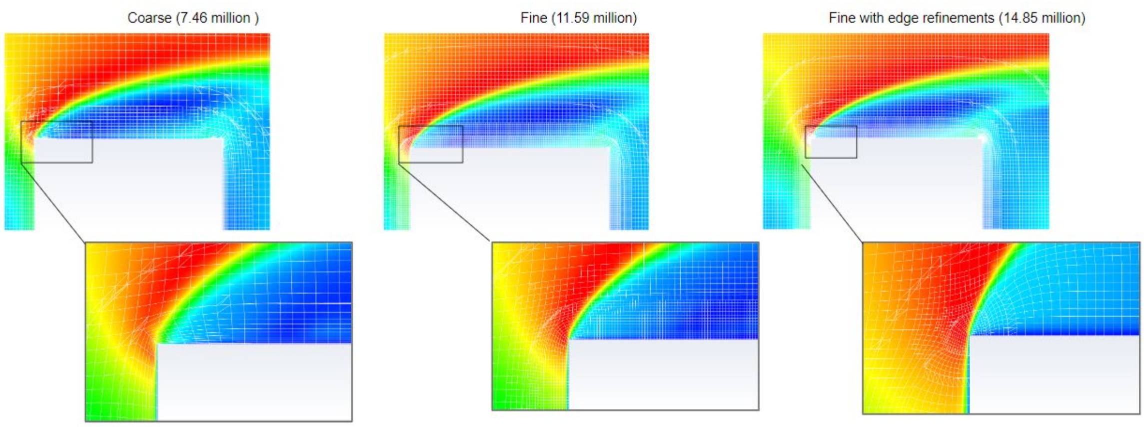


Figure 7. Wind speed profiles for different mesh resolutions near the corner of a building.

2. The CFD model of the D & T Building were used to investigate various sensitivities in conducting a wind study, including the modelling of surroundings, geometric fidelity, discretisation resolution, wind climate modelling, and the number of wind directions simulated. From a practical perspective, it is important to know to what extent a simulation with lower geometric fidelity can maintain an acceptable level of accuracy. This is important because, in order to implement an effective feedback loop into the design process, the approach must be capable of providing early feedback to inform and guide design decisions from the outset.

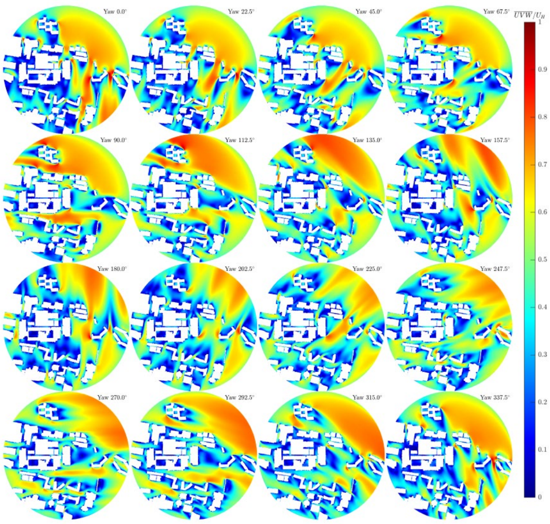


Figure 8. Wind speed profiles for different wind directions in vicinity of the D & T Building (Surrounds case).

To address this, we developed models with progressively simplified geometries using coarser meshes (denoted as "Mesh 1" to "Mesh 3" as shown in Table 1) and compared their predictions in terms of accuracy, computational cost, and turnaround time – the real time required to obtain a solution. The different resolution simulations show a high consistency in predicting surface pressure, while for wind prediction near the test building, the coarser meshes show some limitations, especially in locations where the flow field behaviour is more complex. Notably, the computational cost of "Mesh 3" is over 80 times cheaper than the baseline case of the "Surroundings" configuration, but it still maintains a higher consistency with the most refined case than with the "Isolated" (fine-mesh) configuration.

This strongly suggests that lower-resolution models will be advantageous in the early stages of development to identify potential problems, with higher-resolution techniques employed later for validation as the design crystallises. Consequently, with careful consideration of geometry and wind distributions, simplifications could be made to expedite results early in the design process, guiding the project's direction more effectively.

		Surroundings				Isolated
		Baseline	Mesh1	Mesh2	Mesh3	Baseline
Building Surface Pressure Variance	South	N/A	0.050	0.052	0.081	0.153
	East	N/A	0.060	0.058	0.074	0.134
	North	N/A	0.045	0.053	0.054	0.115
	West	N/A	0.032	0.037	0.050	0.233
	Top	N/A	0.021	0.019	0.033	0.091
Pedestrian Wind Variance	South	N/A	0.027	0.030	0.050	0.104
	East	N/A	0.023	0.025	0.028	0.069
	North	N/A	0.029	0.031	0.051	0.106
	West	N/A	0.027	0.032	0.060	0.142
Cell count (millions)		35.7	12.6	7.1	1.5	32.8
CPU hours per simulation		4000	800	300	50	1500
Estimated wall time (hours) *		250	50	18.5	3.1	93.8

Table 1. An overall comparison of the prediction of pressure and pedestrian wind among different geometric parameters with an indication of the computational cost. (∗: The estimated wall time is based on running the simulations on a 16-core computer with sufficient memory.)

3. Additionally, we explored the influence of wind climate modelling on wind comfort assessment, specifically considering wind uniformity and the number of wind directions included in the evaluation. The study revealed that wind comfort assessments based on the "Isolated" configuration were less dependent on both wind uniformity and the number of wind directions considered. Not surprisingly, the "Surroundings" configuration showed a much greater dependency on wind uniformity. Furthermore, the wind climate is crucial in determining which wind directions are most important. In cases where a significant portion of high winds originates from a specific direction that generates high pedestrian-level winds, the effect is magnified, making it essential to focus on these critical wind directions. This understanding helps prioritise the most impactful wind directions to be addressed in simulations, especially early in the design process, when quick, qualitative results are needed to guide decisions and identify significant issues.

4. Use of more advanced transient simulations were applied (see Figure 7) and it was found that these could be useful in predicting the detailed flow around an isolated structure for a low number of wind directions. However, this is not considered a currently viable technique for most design evaluations because of the computational cost and required duration of these simulations, being an order of magnitude higher than steady models. Nonetheless, circumstances may arise later in the design process where increased accuracy is required from simulations, for example where a specific issue is identified, and in such cases these models may be appropriate.

   While validation showed good agreement between wind tunnel and CFD results for both surface pressures and pedestrian-level winds, some discrepancies were noted. For instance, in certain model configurations, CFD tended to overpredict peak pressures compared to experimental data (see example in Figure 10). However, it is important to recognise that experimental methods also have limitations when compared with CFD, and indeed when compared with field measurements.

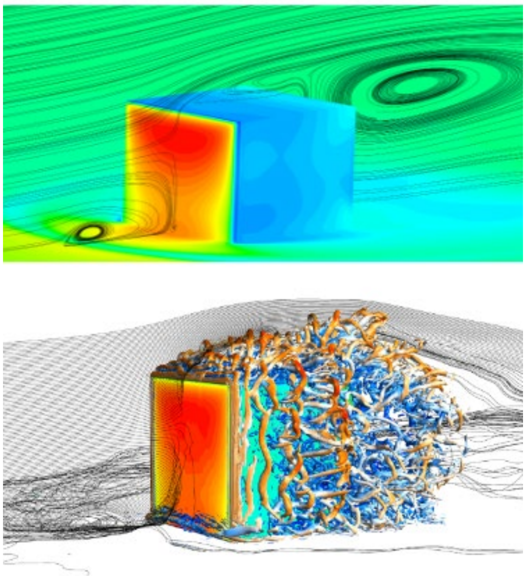


Figure 9. Pressure profiles and flow over the Silsoe cube simulated using RANS (top) and IDDES (bottom).

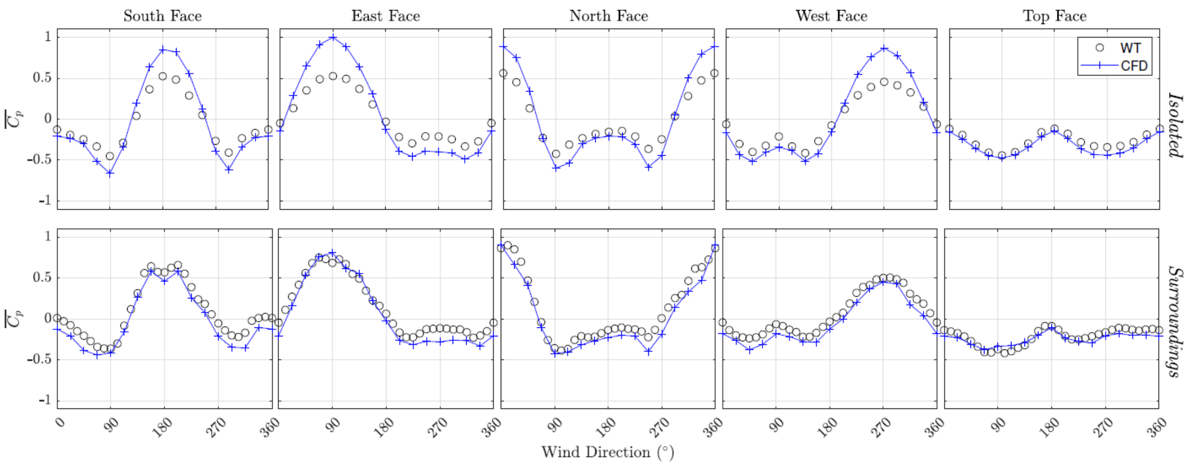


Figure 10. Example of comparison between pressures determined form wind tunnel (WT) and CFD for a selected model.

Wind tunnel measurements, such as those using hot-wire anemometers, require traversing or adjusting the device, which can be time-consuming especially when evaluating multiple wind directions, meaning it is impractical to capture all areas of the flow. Irwin probes, though useful for fixed-point measurements, infer velocity based on differential pressure and perform better in high-speed conditions but lack the ability to resolve wind direction. Additionally, the fundamental difference between how CFD and wind tunnel experiments measure variables, CFD provides detailed flow fields with averaged velocities in three dimensions (as with RANS), while wind tunnels capture specific point measurements, makes direct comparisons difficult.

These discrepancies could stem from limitations in measurement techniques, simulation methodologies, or a combination of factors. Ultimately, even though differences were observed in the magnitude of some output variables, the general trends between the experimental model and the CFD simulations were consistent. This includes the identification of high-pressure zones and elevated pedestrian wind speeds. As such, confidence remains that CFD simulations are accurately capturing the essential flow physics driving these wind effects. It is worth noting that even field measurements present a challenge, as they are often limited by the quality and quantity of available data, and the prevailing wind conditions are typically not well characterised or controlled.

Implications for the Design Process

The process of building design progresses through multiple phases, from a project's conception and design development to construction and commissioning. The detailed design and evaluations required for approvals are often outsourced to specialized consulting engineers when dictated by the project timeline or handed off to the next layer of contractors. As a result, few design materials are retained within the original business that initiated the project, and the asset is typically passed on for ongoing operation without continuity of the design knowledge.

This linear process introduces several key problems, which this project sought to address:

- Delayed verification and testing: Verification and testing of the design are often not conducted until the project is near completion, or sometimes not at all.
- Limited standardisation and commercialisation: It is challenging to standardise, streamline, and automate design processes, as design materials and intellectual property are frequently retained by third parties (e.g., contractors), limiting the potential for commercial reuse.
- Disconnect between design and operation: Continuous improvement in design processes is hampered by the separation between the design phase and the ongoing operation of the building, resulting in missed opportunities for feedback.

This creates a significant issue in the building design process, where lessons from past projects are not learned or applied to future designs or processes. Simulation or testing methods are typically used only during the design phase, and the actual accuracy of these findings relative to the final built state may never be assessed. This can lead to suboptimal design outcomes, where overengineering occurs in some aspects, while critical problems go undetected until late in the project, or even after construction is completed. Moreover, lessons learned from completed projects are not integrated into future designs, preventing the continuous refinement of the building process.

As a pilot study this research project aimed to investigate the viability of a feedback loop pathway (Figure 11) from computer simulation to wind tunnel testing, to built form, and then feeding learnings back into the process. The goal was to speed up design processes by validating computer simulations. For the example building, project outcomes demonstrated a strong correlation between CFD analytical results and wind tunnel findings, even at lower mesh complexities, which reduced computing requirements. This indicates that the section of the model highlighted in green offers a promising pathway for developing and refining a 'lightweight computing' simulation methodology, thus allowing informed design decisions relating to wind comfort to be made earlier in the process.

However, the study lacked 'real world' input from live building measurements, which is a key validation point that still needs exploration. This presents practical challenges for implementation. For developers, the practical execution of a digital feedback loop strategy is more complex in the absence of a dedicated in-house simulation team. Establishing such a feedback loop is complicated by contractual and domain knowledge barriers between the client and design team. Furthermore, developers do not always retain ownership of built structures, limiting the ability to conduct long-term measurement and monitoring needed to provide reliable real-world feedback data.

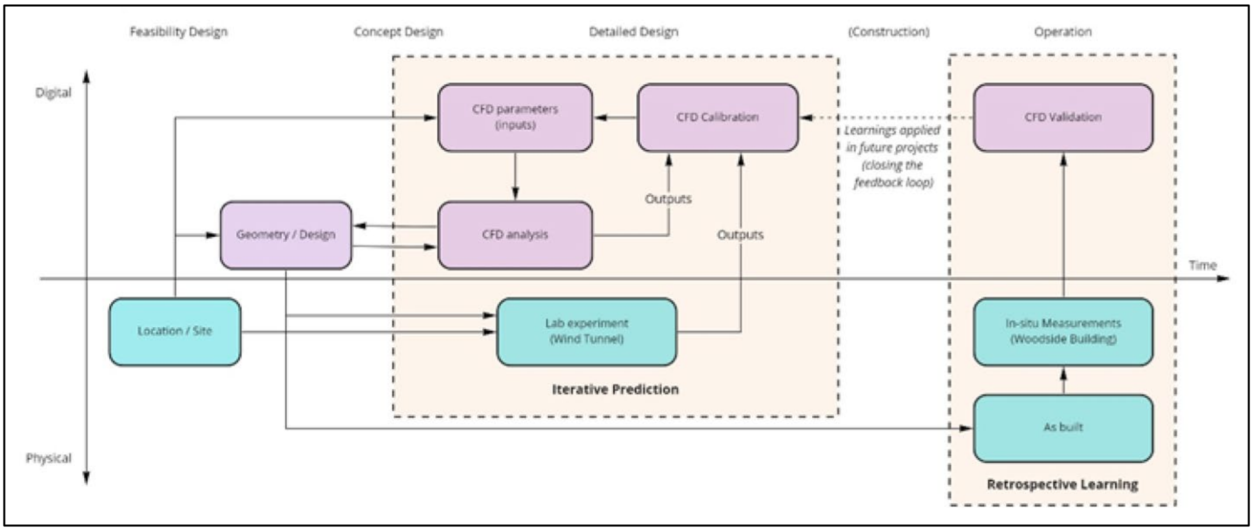


Figure 11. Overview of proposed feedback loop through application of computational fluid dynamics and laboratory (wind tunnel) experiments.

There is potential for further work within the development sector and the wider industry to enhance feedback linkages between the digital simulation space and real-world application. Developers' consultant partners could become 'knowledge partners,' sharing both simulated and measured data from completed and future projects to build a robust and reliable data source. Building owners could also become knowledge partners, incentivised by the potential benefits such learnings could bring to future building designs.

In the short term, developers' consultant partners, who have CFD analysis capabilities and domain knowledge, could be approached to further explore the feedback loop pathway. At the very least, the project has proven the opportunity to generate meaningful CFD output from relatively lightweight computer models, which can be explored as a potential opportunity for integration into broader design platforms.

It is already established that computer simulation of fluid behaviour can inform design outcomes for exterior wind. There is a large opportunity to explore other behaviours of fluids (in the context of the built form) to yield design efficiencies. Ventilation design (both natural and mechanical) are rarely (if ever) simulated through the course of conventional design processes. This carries the potential for unknown over or under-design of components and/or systems. Further, real world measurement of ventilation performance is limited to certain locations in buildings (e.g. thermostats), such that actual performance across an entire building or floorspace is rarely understood. There is opportunity to explore this further in the context of design optimisation but also feedback loop development.

Another example is fire development and spread. Conventional fire design relies upon fire compartment philosophies which are generalised to enable a degree of optimisation of fire design outcomes. When considering the development of a real fire, it is unlikely that the entirety of a fire compartment is impacted from minute one of the fire. CFD simulation of fire growth and spread could lead to optimisation of design for fire (e.g. structure protection requirement). Further, smoke spread could be simulated for various fuel types and quantities to assess risk to occupants in various areas of a building. The opportunities for simulation of building performance are broad, and key to defining the best areas to research will be determining the value generated from refining the 'business as usual' approaches.

Outputs

The key outputs of this work were:

- We developed and optimised a range of IDDES and RANS-based CFD models for efficient and accurate wind comfort studies. These models have been made available to the industry partner.
- We delivered a technical report that has been provided to the industry partner.
- A journal or conference paper is under development, subject to acquisition of additional results (see future work).

Skills, training and education outcomes

The duration of the project was 12 months, which meant that the opportunity for direct educational outcomes was more limited. Nevertheless, this work led to important training outcomes in three key areas. First, significant progress was made in developing early-career researchers, with two postdoctoral fellows playing important roles in the project. Their involvement allowed them to gain valuable experience and enhance their expertise in wind simulation techniques and research methodologies. Second, the project provided hands-on learning opportunities for final-year students, who were actively involved in various aspects of the research. Finally, the results of the project were made available to the industry partner, facilitating the dissemination of knowledge and best practices among their staff.

4. FUTURE RESEARCH PLANS

This section briefly discusses a number of opportunities for further research that have been identified in this project, some of which are underway. This includes the involvement of engineering students that are working to progress the research in the areas where gaps have been identified.

Opportunities for further research

Out of this study, several recommendations arise for further research. Firstly, this project created feedback within the design stages between wind tunnel testing and CFD approaches. However, it is desirable to extend this to instrumenting buildings or examining already instrumented buildings to close the loop between the design stage and operational stage of a structure. An issue in wind engineering design is that there is minimal to no checking of results after the structure is operational, meaning there are currently no broad findings that can be applied to the entirety of the process. This provides an opportunity to extend this work by conducting such an investigation.

Secondly, this study should be extended into other geometries. The D&T Building was chosen through planning discussions with the partner, however, findings may vary for other structure geometries. For example, findings from this structure may not be consistent for a high-rise building (e.g., 150+ m). The D&T Building is approximately 20 metres tall, and a reasonable assumption is that its aerodynamics are dominated by the wind environment in the vicinity of the ground. However, high-rise buildings extend further into the atmospheric boundary layer, and downwash collected from the higher momentum at greater heights forms a significant contribution to pedestrian-level winds. Therefore, the relative importance of different modelling parameters to the overall validity of the results and therefore the appropriateness of modelling approaches, such as near ground geometries and detailed building geometry will be different, to some extent, for these buildings.

A third recommendation is that this study investigated the approach for a ‘standard’ wind study (CFD and wind tunnel studies aimed at the prediction of wind speeds, wind loads, and pressures). However, the impact of the study can be increased by extending feedback approaches through digital modelling into other areas such as HVAC design, ventilation, fire, lighting, and connectivity.

Planned Activities

There are three main activities planned. A final year project investigating the relative performance of different velocity measurement techniques for characterisation of pedestrian level winds, including pressure-based (multi-hole probes and Irwin probes) and hot-wire anemometry. Second, it is intended that this study will provide the additional data required to form a journal publication from this study, at this stage intended for the Journal of Wind Engineering and Industrial Aerodynamics. Finally, we aim to hold an end-of-year (2024) workshop with the industry partner to determine opportunities for expansion of the work given the recommendations described in the previous section. This will also be an opportunity for our students to present their project findings.

5. REFERENCES

Richards, P. J., Hoxey, R. P., Connell, B. D., & Lander, D. P. (2007). Wind-tunnel modelling of the Silsoe Cube. Journal of Wind Engineering and Industrial Aerodynamics, 95(9–11), 1384-1399. https://doi.org/10.1016/j.jweia.2007.02.005

info@building4Ocrc.org
www.building4pointzero.org
/building-4-0-crc