Integrated BIM and VR for Interactive Aerodynamic Design and Wind Comfort Analysis of Modular Buildings

Vincent J. L. Gan 1,*†, Ting Liu 2,*†, and Kexin Li 1

1 Department of the Built Environment, National University of Singapore, Singapore 117566, Singapore; e0537021@u.nus.edu
2 State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, 135 Yaguan Road, Tianjin 300350, China
* Correspondence: vincent.gan@nus.edu.sg (V.J.L.G.); lting_0109@tju.edu.cn (T.L.)
† These authors contributed equally to this work.

Abstract: Modular building is becoming a common sight due to government policies promoting greater automation and productivity. When moving towards modularity, indoor comfort within volumetric modules, such as levels of humidity and temperature, natural ventilation, and air pollutant transport, have a major effect on human health and well-being. Computational fluid dynamics simulations (CFD) are used to evaluate the efficiency of natural ventilation. However, designers usually find it difficult to visualize the CFD simulation results, which can deepen users’ understanding of the wind environment and help optimize the design of modular buildings. To overcome this challenge, this paper presents an integrated approach based on building information modeling (BIM) and virtual reality (VR), with the aim of analyzing the aerodynamic design and wind comfort for modular buildings. The framework consists of four salient components. First, a new method, combining OpenStreetMap and Dynamo, is proposed to achieve rapid urban modeling of modular buildings. The second step involves the use of CFD to simulate the outdoor wind environment surrounding modular buildings. The third step emphasizes the integration of CFD-computed data with VR applications to create an immersive virtual environment for designers to analyze the wind environment of design alternates. Finally, the visual experience of non-professional users is used to improve the ventilation of the building and support more informed decision making at the early stage of building design. The proposed framework is illustrated via a case study that focuses on a group of modular housings in the urban area of Singapore. The results indicate that visualization of CFD simulations in VR provides designers with more details regarding the actual space, and it is expected to help optimize the architectural design.

Keywords: building information modeling; computational fluid dynamics; design optimization; modular buildings; wind comfort; virtual reality

1. Introduction

With the rapid development of global urbanization, problems such as the urban heat island effect and air pollution have become increasingly prominent, which threatens the comfort and health of residents [1]. As an important influencing factor of urban microclimate, urban ventilation can effectively alleviate these problems. In addition, the wind environment has a greater impact on the comfort of residents, air quality, and building energy consumption [2–4], especially in high-density cities such as Singapore and Hong Kong that are in hot and humid climates [5–7]. Modular building is becoming a common sight in Singapore due to government policies and international initiatives promoting greater automation and productivity [8]. When moving towards modularity, indoor comfort within volumetric modules, such as levels of humidity and temperature, natural ventilation, and air pollutant transport, has a major effect on human health and well-being and is a matter...
of concern during the early design. To create the optimal architectural environment, there has been a growing interest in the prediction and evaluation of airflow within modular buildings in the planning and designing stages.

At present, there are two methods commonly used in the analysis and prediction of building wind environment, namely, wind tunnel experiment and computational fluid dynamics (CFD) numerical simulation [9]. Wind tunnel experiment refers to placing aircraft or other object models in a wind tunnel to study the flow of gas and its interaction with the model. However, this method is expensive and requires a long period, which brings great obstacles to practical applications. The CFD method simulates the actual wind environment by solving the aerodynamic equations followed by the wind flow around the building through a computer. With the greatly improved computer operating speed and storage capacity, the simulation of the complex wind environment of modular buildings can be completed in a short period with intuitive simulation results. In recent years, many scholars have compared the simulation analysis results of computer numerical simulations with the results of wind tunnel experiments under the background of simulating the wind environment around the building. The results show that the numerical calculation can better predict the airflow around the building. Due to these advantages of CFD, it is increasingly used in urban-wide wind environment assessment, including urban air pollution [10,11], wind erosion [12–14], thermal comfort [15,16], wind energy [17,18], and other applications [19–21].

Nowadays, there is a growing interest to integrate CFD simulation with a 3D geometric modeling tool that contains the geometrics and semantics (such as material properties) of the buildings to facilitate the creation of analytical models are [22]. A suitable platform is needed to integrate these necessary data. Building information modeling (BIM) is an emerging technology that can provide detailed physical and functional characteristics of buildings, and can solve this problem by connecting information and models at the beginning of design. BIM provides geometric and semantic information of the built environment and is used to set the computational domain and boundary conditions of CFD simulation. Through CFD simulation, the flow field and temperature distribution of the ventilated environment are obtained, and the thermal comfort index of the ventilated environment is determined. In addition, the BIM software also supports the export of different formats for different types of simulations, such as the export of the SAT format required for CFD simulation, which provides a data interface for CFD simulation.

Some scholars have developed an integrated system to simplify the application process of BIM and CFD. Su [23] simulates the architectural layout wind environment of Taipei Shezi Island New City-based on BIM and Autodesk Ecotect analysis software CFD. The simulation results can be fed back to planners and designers to modify the architectural layout to make the building more comfortable and energy-efficient. Utkucu and Sozer [24] developed a method to integrate the three-dimensional scale, energy use, and CFD of buildings through a BIM platform, and optimize building performance by incorporating energy performance and indoor comfort conditions into the building structure. The applicability of the method is verified through a case study, and the interoperability limitation in the data exchange process is determined. Kwok, et al. [25] used BIM technology to build an object-based floor model for CFD simulation and provided geometric, semantic, location, and weather information for solar analysis, and combined solar analysis with BIM to improve simulation accuracy. Weerasuriya et al. [26] established a new framework integrating BIM, CFD simulation, multi-region airflow modeling, and building energy simulation (BES) to accurately estimate the natural ventilation potential of residential high-rise buildings. The combination of BIM and CFD provides timely feedback of key information about the wind environment of modular buildings in the design or operation stage and improves the efficiency of the design and operation and maintenance period. In addition, some scholars have begun to develop an integrated system to simplify the application process of BIM and CFD [27–29].
Although the integration of BIM and CFD can simplify the simulation process, complex simulation results are difficult to understand for non-professionals, and it is difficult for designers to visualize these simulation results. Virtual reality (VR), as the current advanced technology of scientific visualization, can provide users with an immersive virtual environment to interact with objects [30,31]. Therefore, combining VR tools to improve the visualization of CFD simulation results is of great significance to the design and decision-making of all stakeholders in the project design stage. In the past 20 years, architecture, engineering, and construction (AEC) has researched different methods, including virtual reality and augmented reality, to improve communication, visualization, and coordination among different project participants [32–34]. Some scholars have effectively realized the integrated application of BIM and VR. Khalili [35] proposed a novel approach that enables efficient interoperability between BIM and VR, including the geometry of each element as well as the semantic data required for the BIM model. This method has the advantages of significantly shortened transfer time, high-quality rendering and geo-semantic data exchange in design and construction. Du et al. [36] developed a BIM VR real-time synchronization system to realize automated and efficient data transfer between BIM and VR. Shahinmoghadam et al. [37] proposed system architecture for enriching BIM-based spatial representation of buildings in VR environments with real-time IoT surveillance data. In addition, a near real-time calculation of mean radiant temperature (MRT) was achieved using a semi-automated method. Chen et al. [38] proposed a new technology integration framework based on IoT, BIM, AR/VR and developed a prototype system, which can improve the efficiency and management level of building fire safety and rescue. In terms of CFD visualization, scholars have proposed a new building design simulation system that integrates CFD and BIM. The system supports different visualization technologies (such as streamlines or arrows), and stakeholders can more intuitively understand the CFD simulation results, thereby obtaining more comprehensive design feedback [39,40]. Although existing research shows the potential application of VR technology in the field of CFD visualization and wind comfort analysis, research on the visualization and feedback decision-making for urban wind environment, especially regarding the present-day modular buildings, is still lacking.

BIM supports the export of different formats for different types of simulations, such as the SAT format required for CFD simulation. Using BIM software can greatly reduce time consumption and ensure the accuracy of model parameters. At present, most of the development of CFD to VR visualization requires post-processing software such as Paraview, Autodesk 3D Max, Unity 3D for rendering or intermediate format conversion [30,41–43]. This process is time-consuming, and data loss occurs during the model conversion, which affects the designer’s timely analysis and feedback. This study simplified the method of immersive visualization of CFD results by leveraging FBX Exporter to convert the CFD simulation results to FBX format. Following this, the geometric model and CFD computed results are visually rendered and displayed in model rendering software. This process omits the CFD post-processing middleware, which avoids unnecessary data exchange and software incompatibility, improving the quality of virtual visualization and environmental rendering. The results enable stakeholders to analyze the impact of geometric models on the flow field and wind comfort of building design in a virtual 3D environment.

Therefore, this study aims to integrate BIM and VR for interactive aerodynamic design and wind comfort analysis of modular buildings. Our study proposed a framework for designing and optimizing modular buildings through BIM and immersive virtual environments. First, by quickly creating an urban BIM model combined with Openstreetmap and modular buildings. Secondly, by setting different wind speeds, wind direction, and other parameters in the Autodesk CFD analysis software as the initial conditions of the simulation calculation, setting the mixed laminar flow model to simulate the flow of the atmosphere, and obtaining the urban wind circulation analysis results through the simulation calculation in the model. Then external immersive virtual devices observe and analyze the change in the wind field of a residential area. Finally, combined with the user’s
immersive experience in the VR program, the building design is improved to achieve optimal ventilation and user participation in decision-making. The rest of this paper is organized as follows: Section 2 introduces the research methods. Section 4 presents the illustrative example with Section 5 describing the test results and discussion. Conclusions and prospects are presented in Section 4.

2. Methodology

The integrated BIM and VR framework is used to visualize the wind environment in an immersive environment, as well as to evaluate indoor thermal comfort for improving the aerodynamic design of modular buildings. The framework consists of four steps, as shown in Figure 1. The first step is to generate BIM models within the modular layout, which includes the geometry, material, and space information of the modular buildings. The second step transfers the BIM model to CFD simulation software and conducts simulation experiments based on the physical-based modeling of the wind environment for the modular buildings. Before starting the simulation, it is necessary to process the analytical model by dividing the computational domain, setting the boundary conditions, and meshing the geometric models. The third step is to extract CFD-computed data, including the geometric model, airflow field, wind speed, streamline, etc. for the visual display of the wind environment in the immersive virtual environment. In this step, material rendering and data conversion from CFD to the immersive virtual environment need to be set in the VR engine. Lastly, combining the CFD simulation and user experience in the immersive virtual environment is expected to enhance the analyzability of optimizing the modular building design and assist designers to make more informed decision making for the wind comfort at the early stage. The following subsections introduce the methodology details.

Figure 1. Overview of the proposed framework.

2.1. OSM and BIM for Urban Modeling of Modular Buildings

The first step is to generate BIM models within the modular layout by leveraging OpenStreetMap and BIM. OpenStreetMap is a global-level open-source geographic infor-
mation platform, which has the advantages of rich data, open-source, and high timeliness. OSM is a data format generated from OpenStreetMap. This paper integrates OSM and BIM to represent the urban model of modular buildings. The first task of model generation is to parse the OSM file. There are three main elements of OSM, as shown in Figure 2a: Nodes, Ways and Relations. These three primitives constitute the entire map screen. Among them, Node defines a geographic coordinate point by latitude and longitude. The way is composed of 2–2000 nodes (nodes), which can represent three types of graphical elements: non-closed line, closed line, and area. A Relation consists of a series of nodes, ways, or other relations. Each element (such as node, way, or relation) records data information through the Key and Value in the Tag. The key to quickly generating a scene model is to determine the position of the node. The node position in OSM is represented by \( \text{Lat} \) and \( \text{Lon} \), which are the latitude and longitude of the node respectively. Before modeling, it needs to be converted to three-dimensional space coordinates, that is, WGS84 geodetic coordinates are converted to geocentric coordinates. As shown in Figure 2b, assuming that the longitude angle \( \text{AOB} \) is represented by \( \text{Lng} \), the latitude angle \( \text{DOB} \) is represented by \( \text{Lat} \), and the earth radius \( \text{OD} \) is represented by \( \text{R} \), the calculation of the coordinate point \( D \) \((X, Y, Z)\) is shown in formula (1)–(3).

\[
X = R \cdot \cos \text{Lat} \cdot \cos \text{Lng} \\
Y = R \cdot \cos \text{Lat} \cdot \sin \text{Lng} \\
Z = R \cdot \sin \text{Lat}
\]

(1) \quad (2) \quad (3)

**Figure 2.** OSM file parsing. (a) OSM file format, (b) Coordinate transformation.

The whole process of the proposed model generation method is shown in Figure 3. The first step involves processing and exporting the map of the desired area on the OpenStreetMap. Secondly, a scene model generation program is created through virtual programming and python scripting (i.e., Dynamo) within BIM authoring software [44], where the \textit{elk} node package needs to be installed. The GIS data from OpenStreetMap are imported to Dynamo through the \textit{elk} package, thereby mapping the urban model data to the BIM modeling software. Finally, by running the Dynamo program, the surrounding buildings and roads of the large scene are automatically generated in Autodesk Revit to complete the generation of urban BIM models. Although this study integrates OSM data and BIM for urban modeling of modular buildings, the method is generic and can be applied to modeling other types of urban and road scenes.
The urban model generated by integrating OSM and BIM is used as the baseline in this study. On top of the baseline urban model, modular buildings can be further created to support the urban CFD modeling and to study the impact of the wind environment on modular building design. To this end, a modular building project at the Sengkang community in Eastern Singapore is identified and added to the baseline model concerning the residential drawings [45]. Figure 4a shows the layout plan of a modularized flat that contains five modular rooms, manufactured by prefabricated prefinished volumetric construction (PPVC) technology. PPVC can promote the sustainable development of the construction industry and increase productivity by manufacturing independent volumetric modules in factories and by assembling the modules on-site [46]. Each module consists of a frame, floor, ceiling, walls, and other accessories. These independent modules are transported to the site to be assembled into a larger target building structure, which can effectively improve construction efficiency and quality [47]. The modularized flat is assembled to generate the layout plan of modular buildings, as shown in Figure 4b, which includes 10 blocks of 16-story modular buildings. Each modular residential building has been manually light-weighted to remove unnecessary internal building components, and only the exterior (including walls panel, slab, and ceiling) which represents the contact between the building and the exterior environment is retained, as shown in Figure 4c. This is to reduce unnecessary meshing of interior building components and to enhance the efficiency of subsequent CFD simulations without affecting the accuracy of the simulation results. The last step involves mapping of each modular building and the CFD-computed airflow field to VR for representing the wind environment in an immersive virtual environment.

Figure 3. Generation method of architectural scene.

Figure 4. Modular residential buildings. (a) Volumetric unit, (b) Typical floor plan, (c) 3D view.
2.2. BIM-Enabled Aerodynamic Analysis

This study adopts CFD (Autodesk CFD, 2021) to simulate the outdoor wind environment in urban areas. Figure 5 shows the baseline urban model (generated in Section 2.1), as well as the scope of the computational domain where $H_{\text{max}}$ represents the maximum height of the building in the baseline urban model. The study area is $5H_{\text{max}}$ from the upstream as the inlet, $15H_{\text{max}}$ from the downstream as the outlet, $5H_{\text{max}}$ from the left and right sides of the horizontal boundary, and $5H_{\text{max}}$ from the top boundary. The division of the computational domain complies with the CFD best practice guidelines proposed by the Japan Institute of Architecture [48] and is extended according to the COST best practice guidelines [49].

![Figure 5. Dimensions of the computational domain.](image)

Table 1 shows the boundary conditions assigned to the computational domain. The inflow profile of wind speed follows the power-law wind model with a power-law exponent of 0.25, and reference wind speed ($U_{\text{ref}}$) was taken as 2.07 m/s at a height (i.e., reference height, $z_{\text{ref}}$) of 10 m. The profiles of turbulence kinetic energy ($k$) and turbulent kinetic energy dissipation rate ($\varepsilon$) are defined to enable the use of the $k$-epsilon turbulence model. The outlet is associated with the outflow boundary condition, and the top and the lateral boundaries are modelled with the symmetry boundary condition. In addition, a rough surface is leveraged to model the ground. All building surfaces are modelled as non-slip walls. The Reynolds-Averaged-Navier–Stokes (RANS) turbulent model and the $k$-$\varepsilon$ model are employed for the simulation.

**Table 1. Boundary conditions of the computational domain.**

| Location   | Type       | Profiles/Conditions                                      |
|------------|------------|---------------------------------------------------------|
| Inlet      | Velocity inlet | $U(z) = U_{\text{ref}} \left( \frac{z}{z_{\text{ref}}} \right)^{\alpha}$ |
| Outlet     | Outflow    | $\frac{\partial}{\partial y}(u,v,w,k,\varepsilon) = 0$ |
| Right      | Symmetry   | $\frac{\partial}{\partial y}(u,v,w,k,\varepsilon) = 0$ |
| Left       | Symmetry   | $\frac{\partial}{\partial y}(u,v,w,k,\varepsilon) = 0$ |
| Top        | Symmetry   | $\frac{\partial}{\partial y}(u,v,w,k,\varepsilon) = 0$ |

2.3. Integration of CFD-Computed Data with VR

Provided the CFD simulation, the next step is to integrate the CFD-computed airflow field within VR. FBX is a universal model format that supports all major 3D data elements as well as 2D, audio, and video media elements. Existing research has proved its applicability as an intermediate format for CFD and VR software conversion [41,50]. Therefore, this study uses FBX as an intermediate format between CFD simulation and VR rendering.
However, the simulation results from CFD cannot be directly converted to FBX. In this paper, an FBX Exporter embedded within the CFD simulation software is leveraged to convert the geometric model and CFD simulation results. It has the advantage of being able to export CFD results (including particle trajectories, cutting planes, shadow model surfaces, and other surfaces) into FBX for VR scene creation. Provided the FBX file which contains all the necessary geometric model and CFD results, the VR rendering tool is further utilized to create high-quality rendered images for VR scenes. The constructed VR scenes can be packaged and then published to the cloud server for connecting with VR hardware for data visualization.

Figure 6 shows the detailed implementation workflow with all the datasets generated from different phases for visualizing CFD simulation with the aid of BIM and VR. The whole process produces data sets in three different formats. First, the urban models generated in BIM are exported to the CFDST file format and then imported into CFD software for simulation. The second step involves exporting the CFD simulation results as FBX files through the CFD plug-in. After importing the FBX file into the VR rendering software [51], the texture rendering of all objects of the model is carried out by converting the TGA material file that comes with the model into a PNG file. Figure 7 shows the rendering-texture workflow of each 3D object in the geometric model of modular buildings. The added objects include streamlines, cutting planes, and BIM models. It is necessary to set the starting position of the VR scene observation before converting the CFD rendered file to the VR package dataset. Finally, the VR package file is transferred to the cloud platform through the HTTP transfer protocol for unified management and storage. Real-time synchronization of the VR scenes is implemented by connecting the VR rendering software with VR devices. The following subsection introduces the methodology details.

Figure 6. Integrating CFD simulation results with BIM and VR.
2.4. Immersive VR Visualizations

In this study, immersive VR visualizations are performed to verify the proposed methods and workflows. The visualization consists of VR equipment (helmet, two handheld controllers), hardware (workstation and display screen), and other necessary 3D modeling and rendering software. The system architecture is aimed at the whole process consisting of hardware, functionality, and connections between each system element. This research takes Quest 2 as a virtual reality device, which is the second-generation standalone virtual reality headset. In terms of specifications, it is equipped with a Qualcomm Snapdragon XR2 processor and 6 GB of memory, which can ensure smoother performance and generate more pixels to take advantage of the $1832 \times 1920$ monocular resolution. To drive a VR device, a Dell precision 3650 tower workstation with an AMD Radeon PRO W5700 graphics card is applied to drive the VR equipment and conduct the experiments.

After uploading the packaged VR scenes in VR rendering viewer, a series of settings are required to realize the visualization of CFD in the VR device. As shown in Figure 8, the setting of the virtual environment is divided into five steps. First, run the VR rendering software to drive the VR device. Secondly, enter the developer mode and then connect the VR headset (including the VR helmet and two handheld controllers). Fourth, set up in the VR device to allow USB debugging, aiming to fully track the participant’s location and camera angle. Finally, participants can be completely immersed in the virtual environment and interacted with objects and control options in the modular space. Users can use the handheld controller to walk around and point to where they want to go and experience the flow of CFD wind in the virtual environment of urban space.

**Figure 7.** Render-to-texture workflow for every object in the modular buildings.

**Figure 8.** Steps for setting up an immersive virtual environment.
Figure 9 shows the steps of immersive VR visualizations. First, the software application developed by Dynamo is used to create a BIM model of the urban space in Autodesk Revit, including information such as geometry, material, and space usage. The second step is to transfer the BIM model to CFD simulation for pre-processing, airflow simulation, and post-processing. The third step is to extract the CFD calculation results, including geometric model, velocity, streamline, and other data. The CFD simulation results can then be exported as FBX files. The fourth step is to set up an immersive virtual environment combined with VR technology and visualize the designed architectural environment in a VR rendering tool (as shown in Figure 10). Following this, users can evaluate wind comfort by viewing the wind environment of the building space in VR for more informed decision-making. This contains different types of roaming operations, viewing perspectives, and VR modes to move in the 3D scenes to evaluate the wind speed, airflow field, etc., when conducting VR experiments. This further enhances users’ perception of the wind environment of modular building design and improve the analyzability of testing a new design for better wind comfort. Finally, the analysis results are used to optimize the modular building design and achieve the optimal building design or urban morphology.

Figure 9. Process flow of the immersive VR visualization.

Figure 10. Screenshot of the visualization of CFD-computed results.

3. Illustrative Example

Geometric Models

The basic study area selected part of Shenton Way, a one-way street in Singapore’s central business district, as shown in Figure 11a. It is a combination of traffic roads and pedestrian passages, and a combination of shading and sun exposure areas, which has
certain representativeness. The height of the buildings along the street ranges from 1 to 40 floors, ranging from 5 m to 242 m, with a total of 198 architectural objects. The axis direction of the canyon is northeast-southwest. The research area is automatically generated by Dynamo code based on OSM data (as shown in Figure 12). The principle is to automatically generate lines and surfaces by extracting the coordinates, names, attributes, etc. of each point recorded in the OSM file. Buildings with height data will generate cutting height data, and buildings without height data will use the number of floors with a minimum height of 3 m. Autodesk Revit is used to create the BIM models, and the final experimental area is as follows as shown in Figure 11b.

![Figure 11](image1.png)

**Figure 11.** Location and generated model of the basic study area. (a) Site plan, (b) Generated BIM scenarios.

![Figure 12](image2.png)

**Figure 12.** Screenshot of the visual script for generating BIM scenarios.

The basic city model generated by the integration of OSM and BIM is located in the central business district with no modular buildings around. Combining the modular building design method described in Section 2.1, a group of modular buildings is placed anywhere around the basic building group. This group of buildings follows the typical layout of Singapore modular buildings, and the placement follows a symmetrical layout. Combined with the modular design of the new urban area model as the control group to observe the VR visualization effect of the wind environment of modular buildings. To distinguish the two groups of models, we call the basic city model without modular buildings as group one and call the control group with modular buildings as group two. The plan view and 3D view of group two are shown in Figure 13.
The k-epsilon model has a good convergence rate and relatively low memory requirements, so this study uses this model to simulate the urban outdoor wind environment in a three-dimensional steady-state simulation in Autodesk CFD software. The Dell precision 3650 tower workstation was used to perform CFD simulation on the two group models. The computational domain of each group is discretized into a high-quality grid. Group one is divided into 157,818 nodes and 639,897 tetrahedral elements in total, as shown in Figure 14a. Group 2 is divided into 168,105 nodes and 663,550 tetrahedral elements in total, as shown in Figure 14b. The group one urban model reached convergence after 340 iterations, and the CFD simulation result is shown in Figure 15a. The group two urban model reached convergence after 354 iterations, and the CFD simulation result is shown in Figure 15b.
4. Results and Discussion

The magnitude of wind flow from CFD simulation ranges from 2.0 to 2.6 m/s at the ground level for the windward side, which agrees well with the average wind speed of 2.01 ± 0.45 m/s collected from local meteorological services [52]. Due to flow separation, the wind flow decreases to 1.4–1.6 m/s at the leeward side of the buildings. CFD simulation results are mainly for aerodynamic experts, but it is difficult for designers or non-professionals to understand and analyze design practices. This creates a communication gap between various disciplines in the design process. In this study, the simulation results of the urban outdoor wind environment are visualized in VR according to the methods described in Sections 2.3 and 2.4. Before packaging the processed CFD result file and uploading it to the cloud platform, the starting position of the perspective should be added for the user. The simulation results of the model (with modular buildings) displayed in the VR system are shown in Figure 16. In the virtual scene, the user can choose different kinds of viewing modes to observe the CFD simulation results. The immersive virtual environment presents three-dimensional effects in a ratio of 1:1, transforms the invisible wind environment into visible flow lines, and realizes the dynamic immersive analysis of the interactive flow tracker. The pressure gradient is also visualized in the 3D environment to analyze the suction effect of wind on the buildings. The suction effect may contribute to the formation of natural ventilation for modular flats at the leeward walls. Users can walk around in the space, control the direction of advancement through the handheld controller, and observe the wind environment around the building through the movement of the human body. It helps users or architects to better understand the simulation results in complex and non-standard situations, thereby improving the layout of urban buildings.
The basic city model generated in this research is located in Singapore. Singapore has a tropical rainforest climate with long summers and no winters throughout the year. With the acceleration of urban construction, the number of tall buildings in the city is increasing. The high-dense high-rise urbanism increases the challenges of urban air ventilation and purification needs and aggravates the city’s air pollution and heat island effect under low-pressure wind conditions. In addition, when the wind speed is high, strong local winds are generated around high-rise buildings, which affect the comfort and safety of outdoor activities for pedestrians, and even cause a series of wind environment problems for pedestrians and cause economic losses. Therefore, wind environment simulation, on the one hand, can ensure good natural ventilation in the building and meet the requirements of personnel comfort. On the other hand, it can reduce the frequency of system operation equipment (such as air conditioning) and achieve building energy savings. Although CFD can accurately simulate and calculate the three-dimensional velocity field, temperature field, pressure distribution, etc., outside of urban buildings, it provides a limited reference for architectural design, especially the lack of decision support for user participation.

Integrating CFD simulation results within a VR environment provides an immersive experience for designers and enhances the analyzability of testing and optimizing the modular building design, as shown in Figure 17. First, the BIM model is used for static simulation analysis in CFD to optimize the orientation of the building. Secondly, the VR scene provides a dynamic experience and qualitative feeling for designers to optimize the layout plan of the buildings. Finally, the user-centered modular design is realized by integrating users’ experience into the ventilation analysis of urban architectural design. Neither oversized nor small-sized building spacings is reasonable, and VR simulations provide a virtual experience of different spacings together with the wind flow amongst buildings. Through the comparison of different design schemes in VR, users can evaluate the perception of different design schemes, and take user experience as one of the criteria for selecting a better design option. The scenes in VR change with the movement of the participants themselves. This sense of experience is not only dynamic but also continuously changing, and the authenticity is greatly improved. For users, the feedback obtained in this case is more authentic.

![Figure 17. Analysis framework for BIM and VR enhancement design.](image)

This case study demonstrates how to integrate end-user information into the design to increase certainty and end-user characteristics during the design phase. In the VR headset, a designer can apply the hand controller to conveniently adjust the starting position so as to provide better views and walk through the simulated environment. Figure 18a shows an
aerial view of the rendered CFD results about how the wind passes through the modular building blocks and flow to the central business district. Figure 18b shows a ground view and indicates that as the wind passes through the modular buildings, the streamlined color changes from green to light blue to dark blue, which creates a visual impression for the VR user that the wind velocity reaching the back row of buildings is significantly reduced due to the blockage of the front row of buildings. In addition, the wind velocity contour plot indicates that the outdoor wind speed around the windward side of the building is higher than around the leeward side. This immersive experience, therefore, helps the VR user to realize that even with the same room layout, the indoor ventilation of the front building windward units is better than the back building leeward units. Better natural ventilation provides more fresh air and reduces indoor temperatures in summer, resulting in enhanced energy efficiency.

![Aerial view](image1.png)  
**Figure 18.** The wind velocity gradually decreases as it passes through the modular buildings. (a) Aerial view, (b) Ground view. (Wind speed: yellow—moderately high, green—moderately low, light blue—low, dark blue—weak).

Designers and engineers need to pay extra attention to poorly ventilated areas, especially amid the COVID-19 situation. As poor natural ventilation has the potential to cause a build-up of stale indoor air and bacterial growth, which can lead to air pollution. This
can be improved by modifying the orientation and layout of the house, improving the window-wall ratio, introducing void combinations, etc., as shown in Figure 19. It can be observed that due to the construction of the modular building, the wind velocity contour at pedestrian height in the original vacant area changes from green to dark blue, which means that the wind speed changes from moderate to low. This also leads to a significant reduction in wind speed in the windward area of the adjacent building (Area A in Figure 19). The insertion of the modular building also has a clear impact on the pedestrian level wind in the downstream street canyon, e.g., in Figure 19, the wind speed is visibly reduced in Areas B and C. Through the user’s experience of a simulated walk in VR, it is intuitive that the greater the spacing between the two buildings, the better the ventilation. For example, as shown in Figure 20, although Block 8 and Block 9 are located in the downstream area of the modular complex and their ventilation is affected by the front buildings, the ventilation in the aisles between them is better than that of Block 5 and Block 6 due to the greater spacing between them. Therefore, VR users can suggest increasing the too-narrow building spacing to improve ventilation and achieve an optimal design with user participation in decision-making.

Figure 19. Comparison of wind velocity contour plots at the pedestrian level (left—without modular buildings, right—with modular buildings).

Figure 20. Modular buildings marker.

5. Conclusions

This research proposes a visualization integration framework combining BIM and VR, which is used to visualize CFD wind environment information in a VR environment, evalu-
ate indoor thermal comfort, and improve the aerodynamic design of modular buildings. A modeling method that integrates Dynamo visual programming and OSM data is used to quickly establish a basic urban BIM and combined with a modular building construction method to construct a public housing project based on the basic urban model. The two sets of urban BIMs established are processed through the integration of CFD simulation and VR visualization. The framework is applied to the wind environment analysis of a certain urban agglomeration in Singapore, which proves that the developed system can realize the visualization of the thermal environment and can effectively compare various design schemes. In addition, the prototype system can visualize the actual building design, building spacing, thermal environment, and other related information, and provide effective design feedback. From the perspective of non-professional pneumatic experts, it is feasible to integrate BIM and VR to achieve building ventilation design. The system contributes to facilitating collaboration in the building design process, especially between the owner, the building designer and the aerodynamic designer. In addition, the combination of VR and CFD technology provides users such as owners and architectural designers with a more realistic and natural wind environment experience. The visualization of CFD simulation results in VR provides architects with more details about the actual space. This research combines BIM and VR immersive experience and provides more suggestions to realize a new analysis framework based on the user’s intuitive experience. This method of user participation in design can effectively improve the design.

This research focuses on the realization of the whole process of interactive aerodynamic design and wind comfort analysis of modular buildings combined with BIM and VR. The research results show that through the immersive experience in the three-dimensional virtual space, designers can more intuitively feel the flow of outdoor airflow in the urban space, thereby assisting decision-making to improve building ventilation and energy efficiency. However, this study currently only considers the VR visualization display and analysis of the outdoor wind environment. In future research, we will build a more refined modular BIM, combined with the indoor and outdoor wind environment CFD simulation results, to achieve a more detailed virtual scene of the urban building group wind environment in VR. By expanding the application of virtual reality technology in architectural design, the simulation interaction of BIM and CFD can be realized, and the design efficiency can be improved.

Author Contributions: Conceptualization, V.J.L.G.; Formal analysis, T.L. and K.L.; Funding acquisition, V.J.L.G.; Investigation, T.L. and K.L.; Methodology, V.J.L.G. and T.L.; Project administration, V.J.L.G.; Software, V.J.L.G. and T.L.; Validation, V.J.L.G., T.L. and K.L.; Writing—original draft, V.J.L.G. and T.L.; Writing—review and editing, V.J.L.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by NUS Start-up Grant (No. R-296-000-233-133). Any opinions and findings are those of the authors and do not necessarily reflect the views of the grantor.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Wang, W.W.; Xu, Y.; Ng, E.; Raasch, S. Evaluation of satellite-derived building height extraction by CFD simulations: A case study of neighborhood-scale ventilation in Hong Kong. Landsc. Urban Plan. 2018, 170, 90–102. [CrossRef]
2. Zhang, S.; Kwok, K.C.S.; Liu, H.; Jiang, Y.; Dong, K.; Wang, B. A CFD study of wind assessment in urban topology with complex wind flow. Sustain. Cities Soc. 2021, 71, 103006. [CrossRef]
3. Amindeldar, S.; Heidari, S.; Khalili, M. The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in Tehran in cold season. Sustain. Cities Soc. 2017, 32, 153–159. [CrossRef]
4. Du, Y.X.; Mak, C.M.; Huang, T.Y.; Niu, J.L. Towards an integrated method to assess effects of lift-up design on outdoor thermal comfort in Hong Kong. Build. Environ. 2017, 125, 261–272. [CrossRef]
5. Yang, W.; Wong, N.H.; Jusuf, S.K. Thermal comfort in outdoor urban spaces in Singapore. Build. Environ. 2013, 59, 426–435. [CrossRef]
6. Kong, L.; Lau, K.K.L.; Yuan, C.; Chen, Y.; Xu, Y.; Ren, C.; Ng, E. Regulation of outdoor thermal comfort by trees in Hong Kong. Sustain. Cities Soc. 2017, 31, 12–25. [CrossRef]
7. Priyadarshini, R.; Hien, W.N.; David, C.K.W. Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island. Sol. Energy 2008, 82, 727–745. [CrossRef]
8. Almeida, P.R.D.; Solas, M.Z.; Renz, A.; Büchler, M.M.; Gerbert, P.; Castagnino, S.; Rothballer, C. Shaping the Future of Construction: A Breakthrough in Mindset and Technology; Technical Report for World Economic Forum; World Economic Forum: Geneva, Switzerland, May 2016.
9. Blocken, B.; Janssen, W.D.; van Hooff, T. CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus. Environ. Model. Softw. 2012, 30, 15–34. [CrossRef]
10. Solazzo, E.; Cai, X.M.; Vardoulakis, S. Improved parameterisation for the numerical modelling of air pollution within an urban street canyon. Environ. Model. Softw. 2009, 24, 381–388. [CrossRef]
11. Zheng, Y.J.; Miao, Y.C.; Liu, S.H.; Chen, B.C.; Zheng, H.; Wang, S. Simulating Flow and Dispersion by Using WRF-CFD Coupled Model in a Built-Up Area of Shenyang, China. Adv. Meteorol. 2015, 2015, 528618. [CrossRef]
12. Zhang, Z.D.; Wieland, R.; Reiche, M.; Funk, R.; Hoffmann, C.; Li, Y.; Sommer, M. Wind modelling for wind erosion research by open source computational fluid dynamics. Ecol. Inform. 2011, 6, 316–324. [CrossRef]
13. Tominaga, Y.; Okaze, T.; Mochida, A. Wind tunnel experiment and CFD analysis of sand erosion/deposition due to wind around an obstacle. J. Wind. Eng. Ind. Aerodyn. 2018, 182, 262–271. [CrossRef]
14. Hong, S.W.; Lee, I.B.; Seo, I.H.; Kwon, K.S.; Kim, T.W.; Son, Y.H.; Kim, M. Measurement and prediction of soil erosion in dry field using portable wind erosion tunnel. Biosyst. Eng. 2014, 118, 68–82. [CrossRef]
15. Chen, L.; Mak, C.M. Integrated impacts of building height and upstream building on pedestrian comfort around ideal lift-up buildings in a weak wind environment. Build. Environ. 2021, 200, 107963. [CrossRef]
16. Liu, J.L.; Niu, J.L.; Xia, Q. Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort. Build. Environ. 2016, 105, 185–197. [CrossRef]
17. Dhunny, A.Z.; Lollochund, M.R.; Rughooputh, S. A high-resolution mapping of wind energy potentials for Mauritius using Computational Fluid Dynamics (CFD). Wind. Struct. 2015, 20, 565–578. [CrossRef]
18. Yan, B.W.; Li, Q.S. Coupled on-site measurement/CFD based approach for high-resolution wind resource assessment over complex terrains. Energy Convers. Manag. 2016, 117, 351–366. [CrossRef]
19. Janssen, H.; Blocken, B.; Roels, S.; Carmeliet, J. Wind-driven rain as a boundary condition for HAM simulations: Analysis of simplified modelling approaches. Build. Environ. 2007, 42, 1555–1567. [CrossRef]
20. Allocca, C.; Chen, Q.Y.; Glicksman, L.R. Design analysis of single-sided natural ventilation. Energy Build. 2003, 35, 785–795. [CrossRef]
21. Arteaga-Lopez, E.; Angeles-Camacho, C.; Banuelos-Ruedas, F. Advanced methodology for feasibility studies on building-mounted wind turbines installation in urban environment: Applying CFD analysis. Energy 2019, 167, 181–188. [CrossRef]
22. Gan, V.J.L.; Luo, H.; Tan, Y.; Deng, M.; Kwok, H.L. BIM and Data-Driven Predictive Analysis of Optimum Thermal Comfort for Indoor Environment. Sensors 2021, 21, 4401. [CrossRef] [PubMed]
23. Su, Y.M. Incorporation of Computational Fluid Dynamics into the Effect of Building Layout on the Wind Environment-A Case Study of Shezi Island in Taipei. In Proceedings of the World Congress on Engineering 2013 (WCE 2013), London, UK, 3–5 July 2013; Volume 2, pp. 885–890.
24. Utkucu, D.; Sozer, H. Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort. Autom. Constr. 2020, 116, 103225. [CrossRef]
25. Kwok, H.H.L.; Cheng, J.C.P.; Li, A.T.Y.; Tong, J.C.K.; Lau, A.K.H. Multi-zone indoor CFD under limited information: An approach coupling solar analysis and BIM for improved accuracy. J. Clean. Prod. 2020, 244, 118912. [CrossRef]
26. Weerasuriya, A.U.; Zhang, X.L.; Gan, V.J.L.; Tan, Y. A holistic framework to utilize natural ventilation to optimize energy performance of residential high-rise buildings. Build. Environ. 2019, 153, 218–232. [CrossRef]
27. Delavar, M.; Bitsuamlak, G.T.; Dickinson, J.K.; Costa, L.M.F. Automated BIM-based process for wind engineering design collaboration. Build. Simul. 2020, 13, 457–474. [CrossRef]
28. Porter, S.; Tan, T.L.; Wang, X.Y.; Pareek, V. LODOS—Going from BIM to CFD via CAD and model abstraction. Autom. Constr. 2018, 94, 85–92. [CrossRef]
29. Kamel, E.; Memari, A.M. Review of BIM’s application in energy simulation: Tools, issues, and solutions. Autom. Constr. 2019, 97, 164–180. [CrossRef]
30. Yan, J.Y.; Kensek, K.; Konis, K.; Noble, D. CFD Visualization in a Virtual Reality Environment Using Building Information Modeling Tools. Buildings 2020, 10, 229. [CrossRef]
31. Sanchez, C.S.; Zhang, X.Q. Visualization of CFD Simulation Results in VR Environment for Design Feedback. In Proceedings of the Building Performance Analysis Conference and SimBuild, Chicago, LA, USA, 26–28 September 2018; pp. 346–351.
32. Heydarian, A.; Carneiro, J.P.; Gerber, D.; Becerik-Gerber, B.; Hayes, T.; Wood, W. Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. *Autom. Constr.* 2015, 54, 116–126. [CrossRef]

33. Heydarian, A.; Pantazis, E.; Wang, A.; Gerber, D.; Becerik-Gerber, B. Towards user centered building design: Identifying end-user lighting preferences via immersive virtual environments. *Autom. Constr.* 2017, 81, 56–66. [CrossRef]

34. Lin, J.-R.; Cao, J.; Zhang, J.-P.; van Treeck, C.; Frisch, J. Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. *Autom. Constr.* 2019, 103, 26–40. [CrossRef]

35. Khalili, A. An XML-based approach for geo-semantic data exchange from BIM to VR applications. *Autom. Constr.* 2021, 121, 103425. [CrossRef]

36. Du, J.; Zou, Z.B.; Shi, Y.M.; Zhao, D. Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Autom. Constr.* 2018, 85, 51–64. [CrossRef]

37. Shahinmoghdam, M.; Natephra, W.; Motamedi, A. BIM- and IoT-based virtual reality tool for real-time thermal comfort assessment in building enclosures. *Build. Environ.* 2021, 199, 107905. [CrossRef]

38. Chen, H.S.; Hou, L.; Zhang, G.M.; Moon, S. Development of BIM, IoT and AR/VR technologies for fire safety and upskilling. *Autom. Constr.* 2021, 125, 103631. [CrossRef]

39. Hosokawa, M.; Fukuda, T.; Yabuki, N.; Michikawa, T.; Motamedi, A. Integrating cfd and vr for indoor thermal environment design feedback. In Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA), Melbourne, Australia, 30 March–2 April 2016; pp. 663–672.

40. Badias, A.; Curtit, S.; Gonzalez, D.; Alfaro, I.; Chinstead, E.; Cueto, E. An augmented reality platform for interactive aerodynamic design and analysis. *Int. J. Numer. Methods Eng.* 2019, 120, 125–138. [CrossRef]

41. Solmaz, S.; Van Gerven, T. Automated integration of extract-based CFD results with AR/VR in engineering education for practitioners. *Multimed. Tools Appl.* 2021. Available online: https://link.springer.com/article/10.1007/s11042-021-10621-9 (accessed on 26 October 2021).

42. Berger, M.; Cristie, V. CFD post-processing in Unity3D. In Proceedings of the 15th Annual International Conference on Computational Science (ICCS), Reykjavik, Iceland, 1–3 June 2015; pp. 2913–2922.

43. Fukuda, T.; Mori, K.; Imaizumi, J. Integration of CFD, VR, AR and BIM for Design Feedback in a Design Process An Experimental Study. In Proceedings of the 33rd International Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe), Vienna, 16–18 September 2015; pp. 665–672.

44. Autodesk Inc. Revit: Multidisciplinary BIM Software for Higher-Quality, Coordinated Designs. 2021. Available online: https://www.autodesk.com.sg/products/revit/overview (accessed on 20 September 2021).

45. Rahman, M.; Sobuz, H.R. Comparative study of ips & ppvc precast system—A case study of public housing buildings project in singapore. In Proceedings of the 4th International Conference on Civil Engineering for Sustainable Development (ICCESD 2018), KUET, Khulna, Bangladesh, 9–11 February 2018.

46. Zaalouk, A.; Han, S. Parameterized Design Optimization Framework for Worker-Friendly Workplaces in Modular Construction. *J. Constr. Eng. Manag.* 2021, 147, 04021030. [CrossRef]

47. Innella, F.; Arashpour, M.; Bai, Y. Lean Methodologies and Techniques for Modular Construction: Chronological and Critical Review. *J. Constr. Eng. Manag.* 2019, 145, 04019076. [CrossRef]

48. Tominaga, Y.; Stathopoulos, T. Numerical simulation of dispersion around an isolated cubic building: Comparison of various types of k-epsilon models. *Atmos. Environ.* 2009, 43, 3200–3210. [CrossRef]

49. Franke, J.; Hellsten, A.; Schluenzen, K.H.; Carissimo, B. The COST 732 Best Practice Guideline for CFD simulation of flows in the urban environment: A summary. *Int. J. Environ. Pollut.* 2011, 44, 419–427. [CrossRef]

50. Zhu, Y.H.; Fukuda, T.; Yabuki, N. Integrating Animated Computational Fluid Dynamics into Mixed Reality for Building-Renovation Design. *Technologies* 2020, 8, 4. [CrossRef]

51. Simlab. Simlab Composer. 2021. Available online: https://www.simlab-soft.com/ (accessed on 10 October 2021).

52. Meteorological Service Signapore. Climate of Singapore. 2021. Available online: http://www.weather.gov.sg/climate-climate-of-singapore/ (accessed on 15 October 2021).