Exploring potential approaches for integrating microclimate-sensitive design methods within the BIM environment

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ABSTRACT

With the growing importance of microclimate-informed design in achieving net-zero buildings and the widespread adoption of Building Information Modelling (BIM), it is essential to integrate microclimate analysis into BIM. This integration can enhance the design decision-making across multiple scales for urban retrofitting strategies. Despite the critical nature of this integration, progress in the field has been limited. These challenges often result in data transfer issues, delays, and costly reworks. Additionally, the reliability and accuracy of existing interoperability methods are uncertain, underscoring the need for ongoing research to validate efficient integration methods. This paper provides an in-depth review of existing approaches and proposes a novel framework for integrating the most promising Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD) simulation tools integrating microclimate assessment within the BIM environment. The research is divided into three sections: (1) comprehensive microclimate-sensitive design methods on recent application studies, (2) BIM-interoperable CFD simulation software, and (3) promising approaches for integrating BIM and microclimate-sensitive design methods. The research identifies the Rhino-Grasshopper parametric design environment as the most promising for implementing microclimate-sensitive design methods, due to its interoperability with third-party widely validated simulation engines. However, the interoperability of these simulation tools with the parametric design environment of BIM remains very limited. Secondly, the research finds that these widely validated simulation engines provide detailed control over the computational mesh, boundary conditions, and turbulence models, and often provide a closer overall match to experimental data compared to BIM-interoperable CFD tools, showing very small relative deviations in strong wind areas. Finally, the three most promising integration approaches of Grasshopper-component simulation tools within the parametric design environment of BIM are identified and discussed.

Keywords: BIM, BES, CFD, microclimate, interoperability

INTRODUCTION

Urban development is intended to enhance the liveability and well-being of cities by providing physical, economic, and social benefits to citizens. However, contemporary urban design trends are increasingly compromising human comfort and urban microclimate conditions (Core Writing Team et al., 2023). In 2022, the International Panel on Climate Change (IPCC) emphasised the urgent need for a net-zero carbon energy transition by 2050 to limit global temperature rise to below 1.5°C (IPCC, 2023). According to the Science Based Targets (SBT), this requires halving annual CO2 emissions by 2030 and reaching net-zero by mid-century (Heidari et al., 2022). Unfortunately, research shows that most buildings are not energy efficient. For example, the Buildings Performance Institute Europe (BPIE) reports that only 3% of existing European buildings are highly efficient (Heidari et al., 2022).

Adapting existing building stocks for energy efficiency is critical, and net-zero initiatives must integrate this with urban climate adaptation strategies. This approach is

necessary because, as it has been widely demonstrated (Zhang et al., 2023), local environmental factors, such as the Urban Heat Island (UHI) effect play a significant role in the energy performance of buildings. The design of urban spaces influences these microclimate phenomena, which, in turn, impact building energy use (Loh and Bhiwapurkar, 2022). Studies such as (Mehrotra et al., 2020) demonstrate that implementing a combination of mitigation measures is more effective than individual approaches. The influence of urban microclimate on building energy performance highlights the need for models capable of simulating multiple interacting parameters at both building and urban scales (You et al., 2023). Advanced simulation-assisted design methods are necessary to perform these analyses comprehensively. Studying parameters in isolation (i.e., focusing solely on architecture or urban design) often results in incomplete insights (Zhang et al., 2023).

Traditionally, analytical models for simulations have been developed manually from scratch using standalone tools due to fragmentation within the field of computational design (Welle et al., 2011). Despite technological advances and the accessibility of tools, significant challenges remain. These include the time-consuming nature of simulation-assisted design methods and the risk of inconsistencies and inaccuracies when independently developed models are used to evaluate the same project (Welle et al., 2011).

In this context, BIM emerges as an opportunity to develop collaborative work environments where data-rich 3D models of construction and urban planning projects serve as a common multidisciplinary database (Andriamamonjy et al., 2019). Its data-rich structure and standardised exchange formats enable seamless integration of both geometric and non-geometric data (IEA-EBC, n.d.), which are necessary for multiple simulation models (Van Heerden, 2021). This feature makes BIM an invaluable tool for designers incorporating performance simulations into multi-level urban assessments, as highlighted in (IEA-EBC, n.d.). The Annex 91 project (IEA-EBC, n.d.), introduced by the International Energy Agency's Energy in Buildings and Communities Programme (IEA-EBC), serves as a notable example of international efforts to propel BIM technology and methodologies forward. The main objectives of this project are to make energy efficiency a core feature of BIM, establish foundational BIM workflows and data models that promote stakeholder cooperation, and enhance the interoperability of these methods and models both nationally and internationally. Although still in its early stages, Annex 91 aims to overcome challenges in sustainable urban development and contribute to achieving net-zero emissions.

However, BIM design also faces challenges concerning the development of climate adaptation projects in cities. While the progressive implementation of BIM in the sector is giving promising results (Andriamamonjy et al., 2019), there is a significant integration gap between microclimate-sensitive design methods and BIM practices. Although numerous BIM applications have extensive research and current use in energy simulation (Andriamamonjy et al., 2019; Ciccozzi et al., 2023), research on integrating microclimate studies with BIM projects are practically non-existent. In this regard, a construction sector increasingly dominated by BIM implementation policies (Andriamamonjy et al., 2019) is facing fundamental challenges to develop and validate the increasingly demanded UHI mitigation projects at the European level. As emphasised by the IPCC in the 6th Assessment Report, current projects "are not sufficient" to reduce the effect of UHI on cities (IPCC, 2023). A correct multiscale approach to these projects, aimed at improving the microclimate conditions, could not only enhance outdoor comfort but also reduce the energy consumption of building stocks (Lopez-Cabeza et al., 2023), contributing to the achievement of net-zero targets.

Integrating microclimate-responsive design methods with BIM models represents a promising research opportunity to bridge the challenges in each area. Much of the 3D information needed for simulations, such as the UHI effect and Outdoor Thermal Comfort (OTC) assessments, is already embedded in models created by architects and planners (Van Heerden, 2021). Therefore, facilitating semantic interoperability between BIM models and analytical models required for simulation tools can significantly reduce inaccuracies and time in

simulation-assisted design methods (Ciccozzi et al., 2023). This is especially important for microclimate-sensitive design, as it minimises errors common in manually created analytical models for urban projects (Van Heerden, 2021).

However, several limitations and challenges remain, particularly in semantic interoperability between BIM models and analytical models used for stock-scale performance simulations (Gao et al., 2019). The integration of the two primary numerical simulation approaches (i.e., CFD and BES) with BIM is facing serious challenges when translating geometric and semantic information between BIM models and analytical models. In (Maile et al., 2013), common data exchange issues during the generation of analytical models from IFC files are reviewed. These issues arise from discrepancies in how energy analysis data is structured compared to traditional building information (Ramaji et al., 2020). These issues happen at two stages of data exchange between the tools: (1) converting the geometry and attributes from a 3D BIM model into an analytical form, like turning a 3D wall into its surface form for energy analysis, and (2) saving this converted data in a file format compatible with a simulation tool (Ramaji et al., 2020).

This research reviews existing simulation-assisted design methods for multi-scale microclimate impact assessment and state-of-the-art integration strategies with BIM. The review research is structured in three sections: (1) a review of the most widely used state-of-the-art microclimate-sensitive design methods on recent application studies; (2) a comparative review of existing CFD simulation software interoperating with Revit, identifying knowledge gaps and assessing their reliability; and (3) potential pathways for integrating the most highlighted microclimate-sensitive design methods with BIM.

METHOD

This research follows a structured approach to review and evaluate the state-of-the-art interoperability between microclimate-sensitive design methods and BIM. This systematic approach aims to provide novel research on the latest technical advancements to enhance BIM design processes and outcomes through microclimate considerations. The literature review collects the most relevant and recent application studies from ISI Web of Science, Google Scholar, and Scopus, with additional searches conducted on SpringerLink. Relevant studies are selected based on their detailed methodologies, tools, and workflows that demonstrate either promising results on microclimate-sensitive design methods or potential methods for BIM integration, ensuring a comprehensive data collection for further analysis.

The methodology is divided into three steps. First, a statistical analysis of the microclimate-sensitive design methods used in recent application studies is carried out. The results of this analysis are then synthesised into a comprehensive model framework that integrates those tools and workflows demonstrating the best results in microclimate-sensitive design methods. Secondly, a comparative analysis of existing CFD simulation software that interoperates with the BIM modelling tool Revit is conducted. This analysis aims to identify gaps in knowledge and assess the reliability of these simulation tools compared to those identified as the most popular in the previous section. Finally, a novel research review is carried out to explore promising integration pathways for addressing the lack of interoperability between BIM and the microclimate-sensitive design methods highlighted in the first section.

RESULTS AND DISCUSSION

The review results are divided into three sections: (1) analysis of recent microclimate-sensitive design methods; (2) a comparative analysis of BIM-interoperable CFD simulation software; and (3) novel pathways to enhance interoperability between BIM and microclimate-sensitive design methods.

1. Review of microclimate-sensitive design methods

To identify the most promising simulation software and workflows for integration with BIM, we applied the selection criteria described in the methods section to the application studies collected from the literature review. Based on their promising results, 20 application studies were selected as the most significant. We then conducted statistical analyses to show the prevalence of each software and method described in these studies.

Figure 1 presents a statistical analysis of the comprehensive microclimate-sensitive design methods identified from the literature review, grouping them by the following key components: (A) Modelling tools, (B) CFD simulation tools, (C) Simulation outputs, (D) Coupled simulation tools, (E) Additional simulation outputs and (F) Optimisation tools. This figure illustrates the predominance of Rhinoceros as the primary modelling tool in microclimate-sensitive design methods, used by 85% of application studies compared to 15% for Revit. For additional performance analysis, Ladybug Tools' components (particularly Ladybug and Honeybee) are prominently used in 95% of the coupling simulation applications. Butterfly and Autodesk CFD are the most used CFD simulation tools, each accounting for 20%. Among the additional simulation outputs assessed, two main secondary assessments stand out: evaluating outdoor thermal comfort (OTC) using the Universal Thermal Climate Index (UTCI) and assessing solar radiation and daylight.

The results reveal that most of the methods have been implemented in the Rhinoceros software environment using the Grasshopper-component collection of Ladybug Tools (Bedra et al., 2023). Review studies (Hu et al., 2023) have widely highlighted the effectiveness of Ladybug Tools' components, such as Honeybee, Dragonfly and Butterfly, for integrating BES and CFD simulations. Each component addresses a distinct aspect of performance simulation (daylight/radiation simulations and building energy simulations from Honeybee, CFD simulations from Butterfly, and UHI-effect district-scale energy simulations from Dragonfly), providing specialised tools and functionalities to address various aspects of performance-based design. Ladybug Tools stands out above other simulation tool ecosystems due to its ability to create an interoperability network between the parametric design environment of Rhino-Grasshopper and third-party validated simulation engines such as EnergyPlus, Radiance, and OpenFOAM (Bedra et al., 2023).

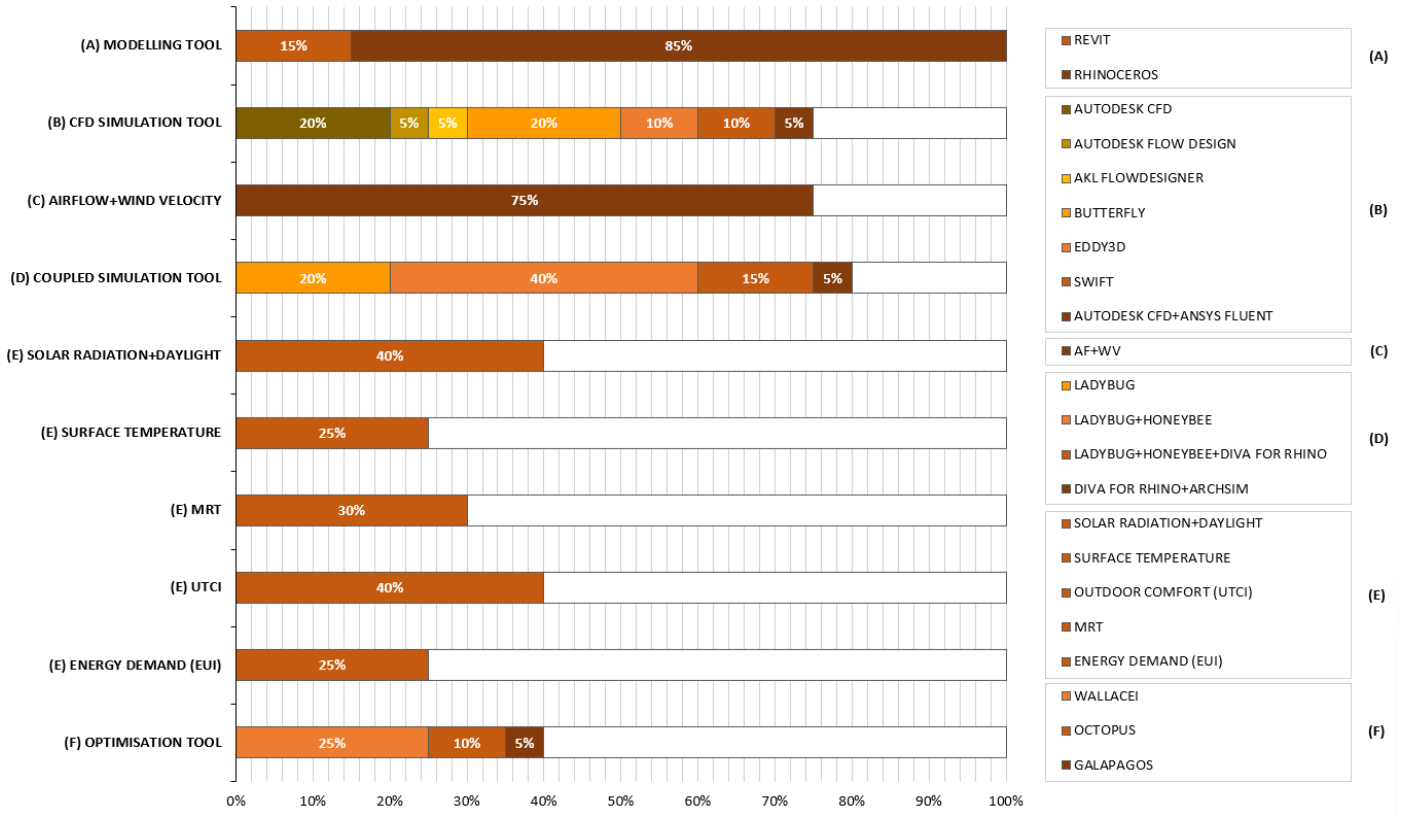

Figure 1: Statistical analysis of key components of microclimate-sensitive design methods.

All the promising simulation workflows identified from the literature are studied, synthesised, and presented in a comprehensive microclimate-sensitive assessment and design framework (see **Figure 2**). Each second-level simulation workflow within the framework is implemented using the most rigorously validated software and outlines the required inputs and outputs for the simulation process.

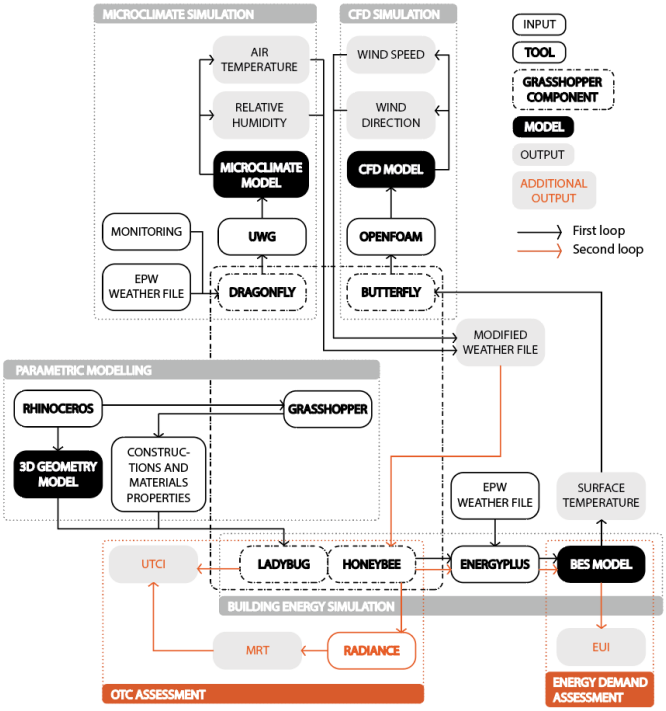

Figure 2: A comprehensive microclimate-sensitive assessment and design framework, integrating the most promising simulation tools and workflows, based on the Grasshopper-component collection from Ladybug Tools

As illustrated in **Figure 2**, comprehensive microclimate-sensitive design methods can involve one or two simulation loops. The first loop (black) represents the initial stage of microclimate simulation, where analytical models are generated from geometry models to calculate microclimate variables affecting local environmental conditions. Once the site-specific microclimate conditions are established, a second loop (orange) of numerical simulations can be conducted to generate accurate additional outputs. This second stage focuses primarily on (a) evaluating OTC conditions using indices such as the Universal Thermal Climate Index (UTCI); and (b) generating analytical models for BES simulations to assess the microclimate impact at the building scale by calculating energy demand through the Energy Use Intensity (EUI) metric.

2. BIM-interoperable CFD simulation software

This section analyses the current state of interoperability of CFD simulation tools and BIM modelling tools. The findings indicate that interoperability between CFD and BIM environments remains very limited. Currently, only three CFD tools are interoperable with BIM modelling software: Autodesk CFD, scSTREAM, and AKL FlowDesigner. The results show that the most frequently used is Autodesk CFD, which supports direct launching from Autodesk Revit via plug-in, making it highly attractive for professionals looking to optimise their BIM workflows. Nonetheless, although less known, scSTREAM, stands out in interoperability, featuring a Revit launcher and the most extensive import format support among the three plug-ins reviewed. Meanwhile, AKL FlowDesigner supports both IFC and gbXML file imports, making it the only tool that covers the two most important data exchange formats for BIM.

Unfortunately, AKL FlowDesigner's capability to import geometry and attribute data from BIM models couldn't be assessed due to the unavailability of a trial version. Likewise, these plug-ins have not been as widely validated as the simulation engines integrated within the Grasshopper environment. For instance, the Grasshopper component Butterfly runs CFD simulations using OpenFOAM, the most rigorously validated open source CFD engine in existence. Urban and building design processes require fast and reliable CFD results within limited timeframes during the design stages, but there is often a trade-off between simulation accuracy and speed when using CFD plug-ins (Hu et al., 2023). The BIM-interoperable CFD plug-in Autodesk CFD is noted for its faster setup and simulation times, making it more user-friendly for those with limited expertise. In contrast, OpenFOAM provides detailed control over the computational mesh, boundary conditions, and turbulence models, which are essential for high-fidelity simulations, as highlighted in (Hu et al., 2023). According to (Hu et al., 2022), OpenFOAM demonstrates superior accuracy in strong wind areas, with a relative deviation on the simulation result of 13.6% from the experimental value, as well as at the highest wind velocity points, with a relative deviation of 7.5%. However, Autodesk CFD performs better in wake wind regions, where the wind

slows down after encountering an obstacle, with a relative deviation of 14.6% (compared to OpenFOAM's 47.2%). To further the application of these tools into BIM projects, future CFD plug-in development should balance accuracy and speed, ensuring reliable and precise performance-based design workflows.

3. Promising approaches for integrating BIM and microclimate-sensitive design methods

Despite the benefits of the popular simulation methods developed within the Rhino-Grasshopper's parametric design environment (see **Section 1**), this promising simulation framework remains largely unintegrated within the BIM work environment, limiting its applicability to advanced urban and architectural design practices currently leading the Architecture, Engineering, Construction and Operation (AECO) industry. In this section, a novel research review is conducted to explore potential pathways for addressing the lack of semantic interoperability between BIM modelling software and most widely validated simulation engines, such as those operating with the Grasshopper built-in components of Ladybug Tools. One primary reason is the lack of direct support for BIM models as input data in Ladybug Tools' simulation components for generating analytical models.

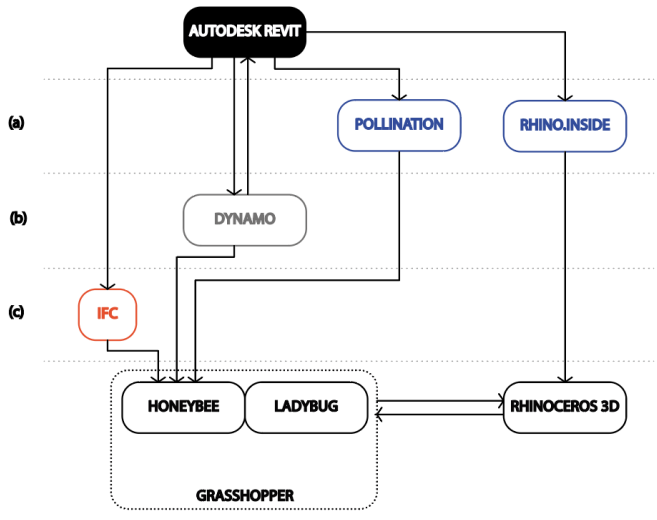

Figure 3: Promising approaches for integrating BIM and microclimate-sensitive design methods, classified into three categories: middleware plug-ins (blue), VPL plug-ins (grey), and BIM-standard exchange files (orange)

Findings from the literature review reveal that promising approaches for integrating BIM and microclimate-sensitive design methods can be categorised into three integration methods (see **Figure 3**).

(a) Middleware plug-ins

Middleware plug-ins (such as Rhino.Inside.Revit and Pollination for Revit plug-ins) shows great potential to overcome traditional data exchange issues on the generation of analytical models from BIM models. Rhino.Inside.Revit allows the launching of Rhino and Grasshopper within Revit. Data can be selected and exported from the Revit model to Rhino, with real-time updates ensuring synchronisation. In Grasshopper, these exported data models can be converted into analytical models. Another promising development in this field is the Pollination plugin for Revit, recently introduced by Ladybug Tools, which leverages the Revit API to generate different analytical model formats directly from the BIM model. It represents a promising direction for integration between Revit and Grasshopper-based simulation engines, such as those from Ladybug Tools. However, this plugin has yet to be fully validated for practical application.

(b) Visual Programming Language plug-ins

Visual Programming Language (VPL) plugins offer another potential integration pathway. Programming and scripting can active a 3D parametric model to evolve into a smarter and more adaptable BIM model. Dynamo for Revit plugin is the most used VPL tool by the AECO industry (Collao et al., 2021). This tool allows the creation of customised scripts to extract and manipulate model data from Revit. Users can define workflows to select elements and properties from the BIM model and use Dynamo nodes to format and export this data into Grasshopper-compatible formats like CSV or JSON. Once imported into Grasshopper, the data can be used to build analytical models and run simulations with Ladybug Tools. No application study was found in this field. Only one study (Khan, 2024) was found that integrates Dynamo for Revit as part of an overview of microclimatic design methods. The study examines the challenges of implementing microclimate-sensitive design methods into current design practices.

(c) BIM-standard exchange format files

Another emerging area of development is the improvement of semantic interoperability between modelling and simulation tools within the BIM environment by creating standardised data exchange formats and methods, such as the IFC schema. Several researchers (Andrianmamonjy et al., 2019) widely agree that IFC-based interoperability strategies hold the most potential for long-term, efficient data transformation. These strategies are based on the BIM-standard exchange format IFC, which is an open standard, independent of any specific software, allowing BIM data to be customised for specific applications like energy simulations. Most IFC-based strategies used middleware tools to transform the IFC file into formats compatible with non-BIM simulation software (Ciccozzi et al., 2023). Despite their success, these strategies still face common data exchange issues during the generation of analytical models from IFC files (Andrianmamonjy et al., 2019), which will be discussed in future work. This review reveals a lack of research on applying these strategies to microclimate-sensitive design methods.

CONCLUSIONS

This research aims to review and identify the most promising approaches for integrating most highlighted microclimate-sensitive design methods with BIM. First, the review of the state-of-the-art workflows for evaluating the impact of design on microclimate conditions highlighted the popularity of Grasshopper-component simulation tools of Ladybug Tools. The Rhino-Grasshopper parametric design environment is the most widely used for microclimate-sensitive design methods due to its ability to integrate urban performance data into parametric design processes due to its interoperability with third-party simulation engines like OpenFOAM via plug-ins such as Butterfly. However, the interoperability of these simulation tools with the parametric design environment of BIM remains very limited.

Second, the review of existing BIM-interoperable CFD simulation tools shows that the current state of interoperability between CFD and BIM environments remains very limited. Currently, only three CFD tools are interoperable with the BIM modelling tool Revit: Autodesk CFD, scSTREAM, and AKL FlowDesigner. However, these tools have not been as widely validated as the Grasshopper-integrated simulation software such as OpenFOAM. Among the BIM-interoperable options, Autodesk CFD stands out for its faster setup and simulation times, making it user-friendly for those with limited expertise. However, OpenFOAM provides a closer overall match to experimental data, and offers detailed control over mesh and turbulence models, leading to higher accuracy, especially in strong wind areas and at high wind velocity points.

Finally, a comprehensive review of potential pathways for integrating the promising Grasshopper-component simulation tools within the parametric design environment of BIM is conducted. The findings reveal that the most promising approaches can be categorised into three methods: middleware plug-ins, Visual Programming Language (VPL) plug-ins, or BIM standard exchange files. Each reviewed approach can be classified into one of these categories, providing a structured framework for analysing and comparing integration approaches in future works. However, the reliability and efficiency of these integration approaches remain unclear and require further research for validation.

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