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Review

Utility of BIM-CFD Integration in the Design and Performance Analysis for Buildings and Infrastructures of Architecture, Engineering and Construction Industry

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Abstract: To scrutinize the current application of building information modelling (BIM) and computational fluid dynamics (CFD) integration in research as well as industrial fields, the present study conducted a holistic review including a bibliometric exploration for existing articles, specific content analysis in different sectors, and follow-up qualitative discussion for the potential of this integrated technology. The bibliometric exploration is focused on analyzing main journals, keywords, and chronological change in representative research content by selecting 115 relevant studies. In content analysis, the representative integrated BIM and CFD application cases are divided into three different sectors. The functionality, interoperability, and sustainability of such integration in architecture, engineering, and construction (AEC) projects are described in detail. Furthermore, the future research based on the applications of BIM and CFD integration is discussed. Specifically, the more advanced hazard analysis is proposed reflecting the strength of such an integration. Comprehensive information for the possible hazards in AEC projects is digitized and quantified to make a more sensitive hazard recognition tool which can formalize reduction strategies and measures of potential hazards. As a result, the present review study contributes to relevant research by identifying representative application parts and practical requirements for BIM and CFD integration in whole design aspects, reviewing the current research trends and future direction in detail, and analyzing the major issues, such as an interoperability in BIM-compatible CFD for sustainable built environments.

Keywords: building information modeling; computational fluid dynamics; building energy performance; HVAC system design; sustainable built environments

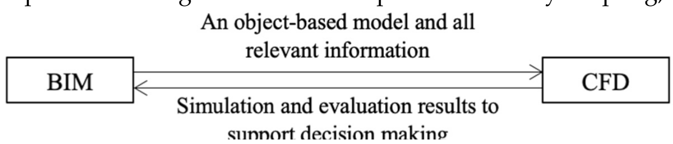
1. Introduction

The architecture, engineering, and construction (AEC) field has witnessed a wide range of advances in recent years, ranging from innovations in construction materials [1,2]; methods of analyzing structural responses to various loads (e.g., seismic [3], thermal [4], and fatigue [5,6]); to the use of computational technologies (e.g., computer vision [7,8] and data-driven techniques [9]). In particular, such scientific advances and information convergence of computational technologies have allowed more efficient design and control of industrial facilities during the entire life cycle. Building information modeling (BIM) is one of them, which offers the professional insight and tools to plan, design, and procure more efficiently and plays an essential role to manage buildings and structures sustainably during the project's life cycle [10]. Hence, recent years have seen an increase in the use of BIM techniques, and practical integrated skills based on BIM are also growing in AEC projects. The main function of BIM is to support the design activities relevant to the project by providing geometry and material properties of the building as well as descriptive information on the building and its components [11,12]. Therefore, BIM-enabled construction design allows not only an improved construction process but also reduced time and costs during the whole life cycle of construction, with systematic data modeling, an interactive visualization platform, and standardized data exchange interfaces [13]. Thanks to the efforts worldwide, the standardization of BIM has been drastically improved since the publication of ISO 19650, which is derived from the UK BIM framework. BIM implementations from the delivery phase to the operation phase of assets are covered, facilitating its wide usage in civil projects.

However, a BIM-supported analysis and decision making cannot fully satisfy the user requirements of the AEC industry. There is a limitation in keeping the sustainability of the building environment, since the construction design process is divided into a lot of stages and a variety of interested parties, often working independently. For example, the data or results acquired from each process require different expertise and background skills and are not centrally managed among all project departments, so that the wrong application of data or information loss issues may occur [14]. Furthermore, cooperation of the models created in programs from one manufacturer is not a problem; however, when there is a need to exchange data between software from different manufacturers, a smooth data exchange may be impossible. To make up for such an issue, the integrated project delivery (IPD) method is now being promoted as a new alternative, which pursues the involvement of all stakeholders communicating and cooperating, pending issues, efficiently through all phases of planning, design, and construction. By adopting the BIM model and a common information model including life cycle data about an as-designed building, the IPD method can be successfully achieved, and it can be used even in various simulations relating to the objective designed building [15,16]. There are a few integrated technologies with BIM tools usually applied in the AEC industry, such as the Internet of Things (IoT) and geographical information systems (GIS). The computational fluid dynamics (CFD) simulation, as a widely used technique for predicting fluid-flow phenomena, is able to describe such engineering events as thermal distribution, ventilation performance, explosion/fire accidents, and its impact on the construction design and building life cycle. Furthermore, the present study focuses on the integrated BIM and CFD technology in the design perspective. Currently, the integrated BIM and CFD-based technology is widely being used in industrial fields, such as the simulation of energy performance, HVAC analysis, and green building design assessment, but there remains an assignment for how integrated BIM and CFD can optimize performance further when considering a demanding building to design. This is because BIM models of architectural spaces are used on a limited basis as the object domain in a CFD simulation, despite the advantages and insight that could be provided [17,18].

Table 1 provides a brief introduction of both BIM and CFD technology, in terms of their concept, elements, and methodology. Essentially, BIM is semantically based and object-oriented, while CFD modelling is procedural-oriented. BIM is used as a communication and collaboration tool for more efficient design and operation during a project's life cycles, but CFD is used as a numerical tool to explore what-if scenarios for specific events based on specific numerical results [19]. On the other hand, a common feature of the BIM and CFD models is precise 3D modeling considering stakeholder's requirements, so that both models can help engineers build and modify the practical design quickly in a parametric way. Due to such a functional difference and commonality, BIM–CFD integration can provide many opportunities to smooth the way for improvements to several applications in the built environment and construction design sectors. Specifically, BIM can provide an object-based model and all the relevant information within a dynamic and integrated platform for CFD simulations. In turn, the CFD simulation and evaluation results can support a wide range of decision making during the life cycle of a built asset, such as design optimization. In this article, we comprehensively review the applications of both BIM and CFD as well as their integration in the AEC industry using relevant research articles published in the last ten years. The status quo and practical applications of BIM–CFD integration are summarized from four points of view: architectural design and building management, energy assessment, Heating Ventilation and Air Conditioning (HVAC) system design, and facility safety management. Furthermore, current limitations and proposals of future research directions are described to provide the roadmap for researchers in studying both BIM and CFD applications.

Table 1. Overview of BIM and CFD technology.

	BIM	**CFD**
Concept	Shared knowledge resources for various information throughout the life cycle of a facility	Digitalized and numerical analysis of fluid-flow phenomena
Elements	Standard data models Life cycle information	Physical model based on Navier–Stokes equations Boundary conditions
Methodology	BIM is implemented and interoperated according to requirements for design planning, construction management, and operation management	A common procedure is followed: preprocessing, solver adoption, and postprocessing, involving discretization methods, pressure-velocity coupling, etc.
Interlink		

2. Review Methodology

To ensure a systematic review of BIM and CFD integration for sustainability, the present review study consisting of five stages was planned. Figure 1 shows the framework for reviewing the technologies, standards, and related publications based on BIM, CFD, and integrated BIM–CFD. In the first stage, the objective of this study was clarified by proposing the scope to explore integrated BIM–CFD technical issues and rules or standards in building designs. The eventual objective of this study was to explore the importance of sustainable building design and to identify how integrated BIM–CFD can optimize performance further in the AEC industry. The second stage was to investigate the evidence, which included publication retrieval, publication filtration, and publication synthetization with the following keyword combinations: "BIM", "CFD", "building energy performance", "HVAC design requirements", and "certified buildings". In the publication retrieval stage, the Google search engine and Scopus website were used to acquire up-to-date and high-quality research articles, technical reports, or conference papers related to the AEC industry that were published by prominent journals or institutions. The publication year was limited to the past 10 years for reflecting the recent trend. As a result, a total of 352 papers were searched from 10 superior journals with an impact factor above 2.5 or strong recommendation of experts. In the publication filtration stage, a detailed examination of searched papers in a previous stage was performed to exclude partially duplicated and irrelevant publication, so that the number of articles was reduced to 115. Turning to the publication synthetization, the filtered publications were organized for analysis and further discussion.

In the third stage, the data were evaluated and analyzed in the findings with the following aspects: common applications; limitation; BIM–CFD integration in complex and challenging buildings; and certified building standards. The next stage was to discuss the effective BIM–CFD integration in sustainable built environments and identify gaps in the existing literature. Thereafter, conclusions were drawn from the analysis and potential opportunities for BIM–CFD integration in the AEC industry were proposed.

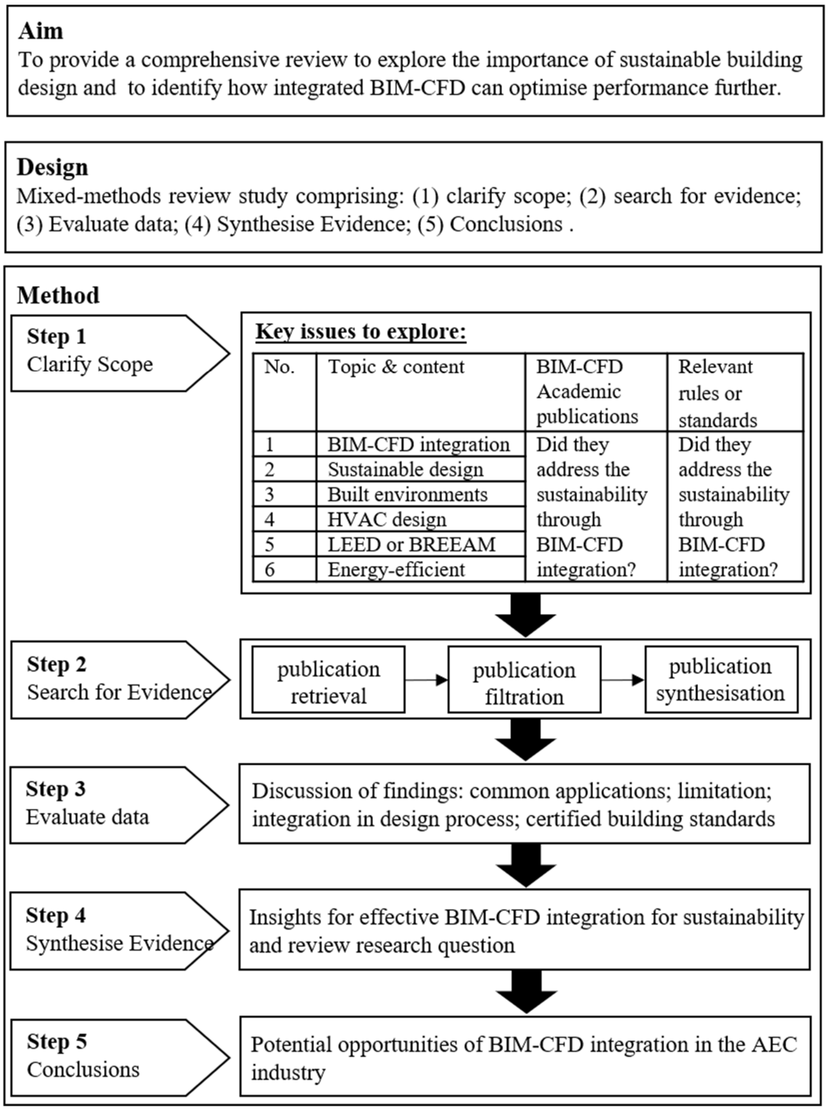


Figure 1. Flowchart of the five-stage review study.

3. Bibliometric Analysis

3.1. Journal Analysis

To search for research articles including BIM–CFD integration, high-quality journals with an impact factor above 2.5 were selected as shown in Table 2. The listed journals spanned a variety of fields: construction engineering, energy section, environmental science, computer science, and civil engineering. BIM–CFD integration technologies were widely used in many fields, but the most frequent application occurred in the construction automation, energy, and built environment sectors.

Table 2. Distribution of the selected papers from different article journals.

Journal Title	Number of Selected Papers
Building and Environment	22
Energy and Buildings	20
Automation in Construction	20
Journal of Building Engineering	13
Sustainable Cities and Society	8
Energies	8
Energy	6

Table 2. *Cont.*

Journal Title	Number of Selected Papers
Journal of Computing and Civil Engineering	4
Journal of Cleaner Production	3
Renewable and Sustainable Energy Reviews	3
Journal of Computational Design and Engineering	2
Advanced Engineering Informatic	2
Applied Energy	2
Computers, Environment and Urban Systems	1
Safety Science	1
Total	115

3.2. Publication Year Analysis

To reflect the latest research trends, the range of publication year has been limited between 2012 and 2020. Figure 2 chronologically shows the number of total articles between 2012 and 2020 as well as the number of articles in each topic. The figure clearly indicates the research using integrated BIM and CFD technologies started in 2012 and experienced a fluctuated growth until 2017, but predominantly increased in the recent 3 years. A similar pattern has been observed even in subject-based classification. This indicates the rising interest of researchers in this field of study over the last decade. Nevertheless, the number of papers on the application of integrated BIM and CFD research is still relatively small compared with the conventional research usually drawing attention in the relevant fields, such as computational techniques and applications, architectural design, and information management. Therefore, there would be many opportunities and much potential in the future study of this area.

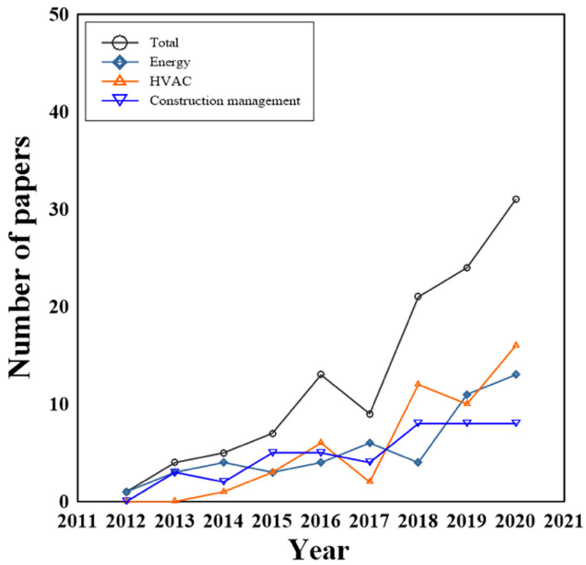


Figure 2. Chronological comparison of research articles using the application of integrated BIM and CFD integration.

3.3. Keyword Analysis

The bibliometric analysis in Scopus was conducted to find the co-occurrence keyword and to set apart articles that were not included in the present scope. By using the VOSViewer program [20], 115 selected papers were used and the keywords with a frequency of greater than five were selected for the co-occurrence analysis, so that graphical network visualization as shown in Figure 3 was obtained. In the figure, the node size of corresponding keywords indicates the frequency of them in selected articles, and the distance between each node indicates their closeness of collaboration. Based on the bibliometric analysis results, a framework of the present study was modeled, including current research trends; specific applications in ACE industries, especially in architectural design and construction operation; and energy performance analysis. Table 3 shows the related research fields widely using integrated BIM and CFD skills. For each sector, representative research work and interest are delineated comprehensively in the next section.

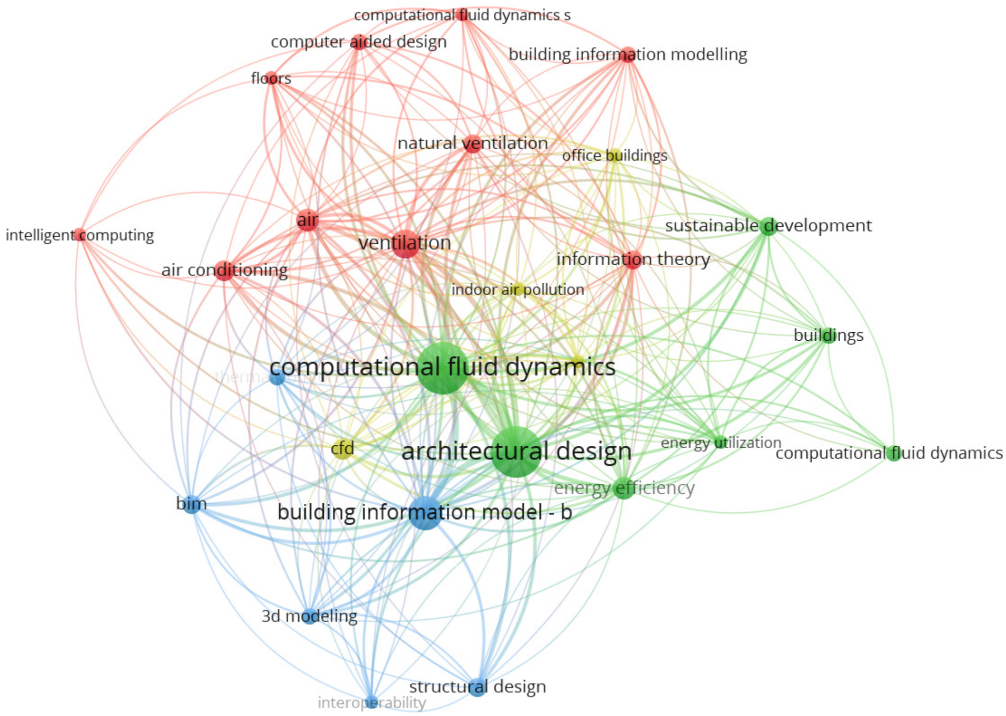


Figure 3. Categorized keywords associated with BIM and CFD integration.

Table 3. Categorization of selected articles by topics.

Sectors	Subsectors	Related Research
Architectural design and building- management	• Building operation and maintenance • Architectural design optimization for sustainability • Construction information management and process monitoring	[21–28] [29–41] [42–50]
Energy assessment	• Energy consumption/performance evaluation • Energy model development to assess flow/efficiency • Certified green building process	[51–61] [49,50,62–78] [79–92]
HVAC system design	• Thermal comfort/heat transfer • Air/wind (flow and quality) and ventilation-system • HVAC system	[21,27,33,34,42,43,93–110] [22,23,29–31,44–46,111–127] [128–130]
Facility safety management	• Disaster simulation and emergency response	[106,131–135]

4. Analysis of BIM and CFD Integration in Different Sectors

The CFD model is normally used in the design of buildings to simulate the thermal comfort of occupants and ventilation performance, the consequence of fire, air flow around a site, and so on. Such simulations are performed considering the detailed geometry condition, material properties, and loading/boundary/environmental condition with a few different scenarios, and the results can be used to assess building performance under normal operating conditions as well as unfavorable conditions. Therefore, integrated BIM-CFD technology can make possible smarter construction and more energy efficient buildings.

Hence, there is an increasing number of CFD applications which integrate with BIM tools. Using a combination of BIM and CFD simulation is particularly required when simulating complex and challenging buildings such as indoor facilities, grow rooms, and LEED or BREEAM certified buildings. This is because it is quite demanding to understand the flow inside or around such buildings. The application of BIM and CFD integration is discussed from the following four sectors, as indicated in Figure 4.

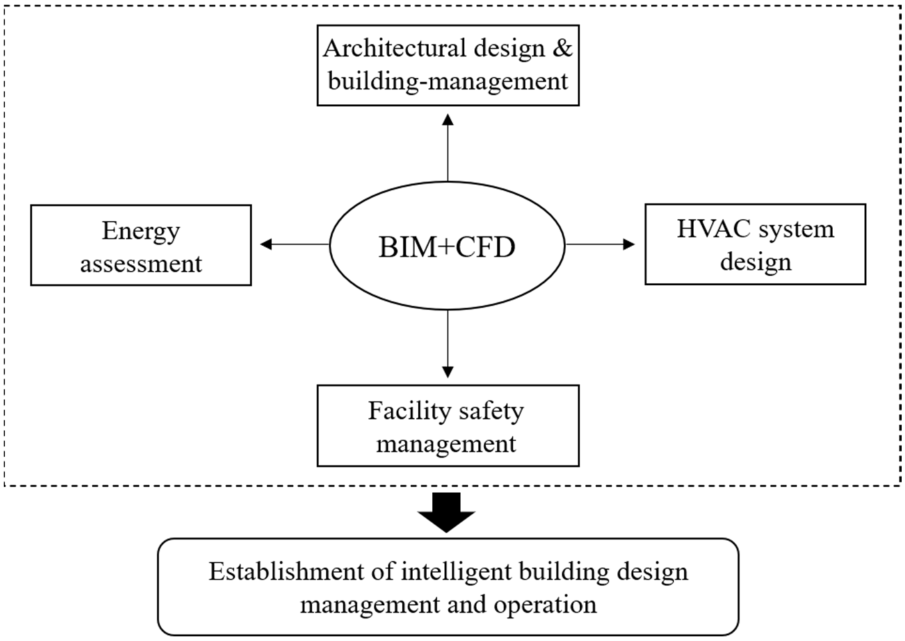


Figure 4. Key application of BIM–CFD integration.

4.1. Sector 1: Architectural Design and Building Management

The ACE industries have experienced continuous development of computational technologies. The BIM-compatible CFD brings design optimization, particularly in complex and challenging buildings. For example, the high-rise building design requires a CFD analysis considering local climate and wind loads because such loads can influence building safety. CFD analysis results include climatic and topographic information and are exported and outlined with the BIM model. The integrated BIM and CFD can also play an integral role in building management sectors by assisting the operation analysis as well as the performance evaluation. Moreover, such consolidated technology can provide extensive information resulting in a more effective architectural design process and facilitating smarter construction and facilities management, so that it can be used in various fields as follows:

4.1.1. Building Operation and Maintenance

To effectively maintain building performance, it is required to monitor the indoor environment such as air quality, and the building's thermal, ventilation performance, and energy consumption [21–23]. Those conditions are also causally linked to the wellbeing of its occupants. By adopting the CFD model, a complicated building structure can be digitally constructed reflecting the accurate geometry condition, material properties, and other information associated with the on-site environment. Herein, the BIM technology is used to provide an object-based model for CFD simulation, and then the integrated BIM and CFD model can be used for building performance analyses, which calculate temperature distribution, coupled outdoor wind flow and indoor air flow, and so on [27,28].

4.1.2. Architectural Design Optimization for Sustainability

Since the potential environmental impacts significantly influence the entire construction project, sustainability is a major issue in terms of both design optimization and a building development in AEC industry. The purpose of each design is different, but the common objective is to achieve a sustainable design environment within time and cost. While the best opportunities for assessing building environmental performance or relevant design issues occur in the early design stage, the simulation for performance evaluation is usually conducted at the end of the process, so that the finding or results acquired from simulation are often not integrated into the design decision-making process [36]. Hence, incorporating a BIM-based design support has been increasingly used in the early stages to prevent late design changes that may cause additional costs and project delays. The use of CFD in the early stages could be one of the best options for design optimization in a sustainability built environment. The early CFD evaluation of building energy consumption can provide decision-making options based on accurate information regarding the selection of window configuration or material composition to effective thermal distribution in buildings, and it ends up preventing excessive energy consumption in the building [23–25]. Incorporating a BIM-based performance design support has been increasingly used in the design stages, allowing designers to efficiently select optimal design options for their projects [72]. Early integration of building a thermal performance analysis can support more informed decisions regarding the selection of building enclosure materials to prevent overall excessive heat flow into buildings.

4.2. Sector 2: Energy Assessment

A lot of researchers have tried to use the BIM and CFD integrated method in technical analyses required for more energy efficient buildings. CFD is normally used as a reliable validation tool to obtain detailed insight into the air flow pattern, energy consumption and efficiency, and more. It can be highly beneficial for the planning of energy efficient building designs and obtaining a green building certification, where optimized energy performance and air comfort play a crucial role since a set of data associated with flows like pressure, velocity, and temperature in a specific space can be obtained through the CFD simulation. The major issues in this sector are divided into three categories: energy performance evaluation, model development, and green building design, respectively.

4.2.1. Energy Consumption/Performance Evaluation

According to Reference [54], 48% of the total global energy is consumed by buildings every year, among which operation energy accounts for over 80%. Accordingly, many experts put efforts into developing technologies that measure energy consumption and end up being possible to reduce energy costs of buildings. Since a CFD analysis can provide detailed information on the amount of energy, pressure, air composition, and heat transferred in the building, many researchers tried to propose energy management solutions through the reliable analysis and validation. These studies were related to: evaluating building energy performance with CFD results as specified by temperature, humidity, and air condition [53,58,59]; proposing the better design option of insulation systems by comparing several design features from the geometrical shape to configuration [51]; verifying the effectiveness of experiments to observe the optimal design in energy efficiency aspects [61]; integrated monitoring, analysis, and control methodologies for reducing waste and saving energy [73,74]; and the development of building energy simulation models based on design information [66,72,78].

In conclusion, the integrated BIM and CFD model enabled the benefits of time, cost, and energy savings in a comparative analysis of building performance. However, a modification tool between the BIM authoring tool and CFD analysis program is required for more reliable energy simulation since data loss might occur by an interoperability deficiency. It would be possible to propose a more accurate energy performance evaluation model and relevant simulation results with a single integrated building performance tool if the data exchange is smoothly conducted and the interoperability issues are resolved.

4.2.2. Green Building Design

Globally, buildings consume a lot of energy, so the AEC industry is pursuing energy efficiency strategies. Hence, green building design and environmental-friendly design are becoming increasingly popular and even being taken for granted in a construction site. Green building certifications such as Leadership in Energy and Environmental Design (LEED) certification of U.S. Green Building Council (USGBC), Building Research Establishment Environmental Assessment Method (BREEAM), as well as the Standard 189.1, are intended to outline and confirm that a building meets a particular standard and offers an environmental benefit [86,87,90]. Thus, several assessments and a certification procedure are required to achieve a goal of green building. Several categories for green building certification include design aspects relevant to operations and maintenance optimization, making it imperative for mechanical, HVAC system, building, and sustainability designers to find the right combination of design strategies. In that regard, having an optimal HVAC system is necessary since it determines the building's energy efficiency, life cycle performance, as well as healthy environments for occupants to live and work in [88,89].

To ensure an optimal HVAC design with relevant green building standards, a reliable validation tool needs to be used during early design stages. The CFD analysis is one of them and predicts air pattern, thermal distribution, humidity, and contaminant concentration accurately, so that it can assess the air quality both indoor and outdoor considering the building design information [91,92]. Therefore, the studies in this sector mainly focused on the numerical study to investigate the effect of ventilation systems on the indoor thermal comfort of a residential building [79,80,85]; the estimation of potential wind state and evaluation of the ventilation rate based on CFD analysis results [81,82]; and the investigation of buoyancy-driven air flow in different ventilation strategies with thermal simulation along with air flows in a building [83].

4.3. Sector 3: HVAC Design Requirements

As the importance of HVAC optimal design in buildings increases, the high-tech application for better HVAC performance is becoming more prevalent. The goal of the HVAC system design is to create optimal indoor environments inside the building while minimizing energy consumption, so that these systems help to create an energy efficient building as well as a resident-friendly building. As it relates to HVAC design, CFD is best suited to design complicated spaces within a building since a 3D numerical model reflecting detailed geometry conditions can be used to simulate the thermal or ventilation performance of such buildings. CFD analysis results provide engineers or designers with a cost-effective and insightful tool to better understand key issues associated with HVAC design, while also providing authorities with suitable data to evaluate whether the design parameters meet regulatory guidelines or construction objectives.

BIM is used as a platform to integrate all information and apply a spatial analysis. In each of the key applications across the HVAC design sectors, the use of the BIM and CFD integrated approach provides engineers and designers with the right tool in the following areas.

4.3.1. Thermal Comfort/Heat Transfer Assessment

The thermal comfort analysis is now an integral part of the design process of residential buildings, especially to demonstrate compliance with the building standards or regulations. CFD models for the thermal analysis can provide accurate thermal distribution data for a set of defined input parameters. Hence, a lot of studies have included a CFD analysis in the building design process to investigate the thermal performance, construction defects, as well as thermal comfort inside of buildings [21,33,43,96–98,101,102]. In Ref. [96], the predicted percentage of dissatisfied (PPD) and predicted mean vote (PMV) have been visualized with CFD software to identify flaws with the heating system considering several temperature conditions. Resident area and the amount of time people stay in this area were considered for a more correct assessment of thermal comfort with specific building interior conditions. The authors of ref. [21] used CFD simulation on an office floor for improving simulation accuracy by coupling a solar analysis with the BIM technology. The BIM technology provided relevant information for the solar analysis, such as semantic location, geometric condition, and weather information, and then solar heat acquisition and distribution on curtain walls were estimated through the CFD analysis considering that information. The authors of ref. [102] carried out CFD-based thermal simulation to analyze the behavior of the active transparent facade (ATF) when combined with a mechanical ventilation system and the thermal effects this system produces inside of buildings. In addition to the above applications, CFD simulations are used to visualize the melting process of the phase change materials (PCM)-filled structure and investigate strategies to improve thermal energy storage efficiency [97].

4.3.2. Air/Wind (Flow and Quality) and Ventilation Analysis

Ventilation systems play a key role in the air quality improvement of buildings, so a well-calculated ventilation system design is required for a successful building design. Optimizing the ventilation system design is an increasingly challenging process as both the complexity of the building layout and the range of functionalities included in the system expand, and design flaws of this part can result in an inefficient energy consumption, as well as lower engine performance due to excessive pressure losses or distortion [128–130]. In this sector, CFD simulations can be used in understanding and optimizing the air flow through the complete ventilation system, including its air filter and ducting. Since a CFD analysis of the BIM-based model can help by suggesting various geometrical changes, a series of analyses can be performed considering such design options [23,111–113,117,120,122]. The CFD models described in ref. [114,118] analyzed the ventilation rate, air flow patterns, and mean surface pressure coefficients for a building considering several wind directions based on the Reynolds-averaged Navier–Stokes approach. The authors of ref. [30] carried out a parametric study using a CFD analysis for investigating the influence of different building geometry modifications on pedestrian-level wind patterns, and even the coupled modeling method to calculate air flow around the outdoor and indoor simultaneously can be implemented by CFD simulation as described in ref. [119,126]. In addition, the air quality can be estimated based on CFD simulations which visualize contaminant concentration in the air or pollutant dispersion in the built environment [45,121].

In conclusion, the HVAC optimal design is directly connected to energy efficiency and green building, so accurate numerical calculation considering specific building information should be required in each design process.

4.4. Facility Safety Management

To achieve safe building environments, design teams should investigate the alarming situations or undesirable cases and prepare the mitigation actions against such events through the whole design process. The BIM and CFD simulation can be a more effective tool in analyzing a disaster and a hazard scenario compared to the experimental studies, since it is cost effective and not related to safety issues, which could occur in real field tests. Fire hazards are regarded as the most frequent and dangerous situation to human life and property safety, and the scale of fire damage varies depending on the environments such as the level of density, constructed material, and the types of buildings. Although a thorough analysis for fire hazards is required in a design process, the experimental method to investigate the fatalities and the level of property loss during a fire is not realistic and unethical.

CFD simulation is an insightful tool which can provide useful and effective information in such analyses. It can not only investigate many different scenarios but can also repeat the same analysis with little extra effort. The consequence of a fire depends on many variables, but fire simulation using a BIM-based CFD model can reflect this complexity with more realistic and accurate input data. In addition, the densely occupied area can be precisely modeled by importing the 3D aimed model. The specific method and practical application of BIM–CFD integration for building safety management is described below.

Fire Simulation and Emergency Response

BIM–CFD integration can be applied to the fire-resistant design of buildings. For example, it provides safe and reliable methods of fire modeling in the design phase. In this sector, BIM has been usually applied for effective evacuation planning in the buildings during emergency situations, while CFD has been used for describing the specific fire scenarios and calculating the fire loads acting on the structures, so that building integrity can be predicted under the assumed fire case [133–135]. Therefore, the integrated BIM and CFD model can offer a reasonable dataset for more effective configuration design and material design in such disasters. The authors of reference [132] used the CFD model to simulate the potential fire incidents and smoke scenarios, and the integrated BIM–CFD model allowed the prediction of a rescue scenario from the exterior of the building during a fire and the proposal of an optimal path in that situation. A post-earthquake fire simulation conducted in ref. [131] analyzed the spread of fire assuming the damaged sprinkler systems by seismic loads. By converting the BIM into the CFD model, a high-fidelity numerical model of a building and its sprinkler system was created in the fire dynamics simulator program.

In conclusion, the existing research for emergency response using the BIM–CFD integrated model is usually focused on the qualitative evaluation, but the quantitative analysis for potential hazards is also required to assess the corresponding risks extensively.

5. Discussion and Insights for Effective Adoption of BIM and CFD Integration Technology

5.1. Integrating Quantitative and Qualitative Hazard Analysis Based on BIM and CFD Integration

5.1.1. The Fundamentals of Hazard Analysis

Hazard is usually defined as a source of potential damage, which means all situations leading to undesired events. Hazards of facilities in AEC industries include abnormal high pressure or temperature in any operation system, the occurrence of smoking in a dangerous area, flammable materials, and storage tanks with toxic substances. It is important to note that ‘hazard’ indicates potential damage or harm, not a realized one. The purpose of a hazard analysis is to ensure this very potential damage does not appear, and if the damage does appear, then mitigation methods are required. Several activities are included in the hazard analysis procedure, but hazard assessment is a key issue in the construction design process, since it means identifying the extent of potentially dangerous events which must be managed adequately. Figure 5 shows the typical hazard management process. The methodology for the hazard assessment can be categorized into two types: quantitative and qualitative approaches. At first, the quantitative hazard assessment is a systematic approach of identifying a major accident hazard with its likelihood and consequences. This methodology is usually required for production or process facilities including extreme operational environments such as oil and gas, mining, automotive, and flight structures. The results are expressed quantitatively for how a certain hazard is dangerous to people, the environment, and other properties. The validity of quantitative results is assessed by identifying key assumptions and hazard driving factors. Acceptable hazard criteria could be required if there are significant changes to system operations or major hazard plant construction plans.

On the other hand, a qualitative hazard analysis is used to qualify the hazards relating to a particular event. It also uses the frequency and consequence concepts even though they are not numerically estimated. Instead, each indicator is assessed by verbal expression, such as high frequency and low frequency. It may often be difficult to provide the exact numerical outputs for probability distribution or consequence estimation for a certain hazard with the quantitative approach. However, the qualitative assessment can be a good substitute for hazard screening and comparing several alternatives in this situation. In this chapter, the new approach for a hazard analysis using the integrated BIM and CFD principles is proposed.

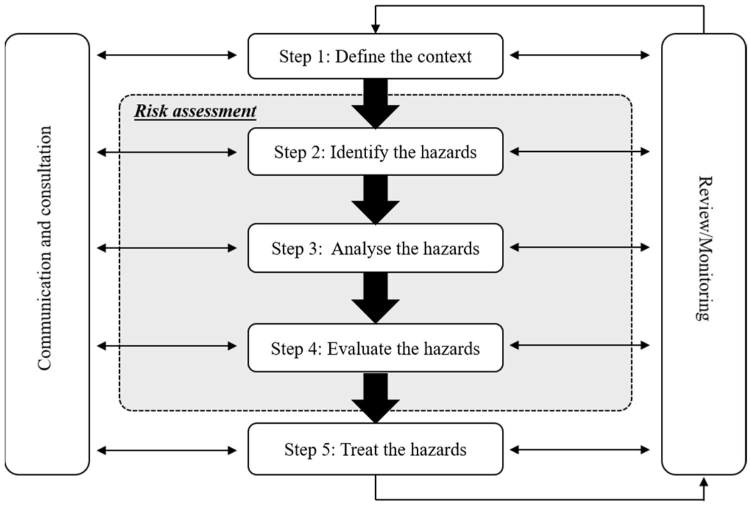


Figure 5. The procedure of typical hazard management.

5.1.2. Application of Integrated BIM and CFD for a Comprehensive Hazard Analysis

Most construction projects are large scale, and each process is divided into multiple stages, so that a lot of departments and parties work independently. The data or results acquired from each task are not centrally managed among all relevant departments, and the ability to execute any design changes can be time consuming or even impractical due to a communication problem or work proficiency gaps. A lot of computational technologies have been developed to link the different departments and to manage a huge amount of data efficiently for different purposes, but herein the BIM and CFD applications for the hazard analysis are the only ones focused on. BIM is used as a communication and collaboration tool for more efficient design and operation during a project's life cycles, and CFD is used as a computational tool to explore what-if scenarios based on specific numerical results. Therefore, quantifying certain events in a hazard scenario is more compatible with a CFD approach, while qualitative hazard analyses can flourish with the BIM tool. A common feature of BIM and CFD technology is that precise 3D modeling can be constructed considering the stakeholder's requirements, so that both models can help engineers build and modify the practical design quickly in a parametric way. Therefore, a more exhaustive hazard analysis could be conducted when applying such attributes of BIM and CFD.

In the conceptual design stage, a hazard is associated with how the design strategy has feasibility considering the secured budget, construction purpose, and established governance regime, and that is an area where BIM has the strength in managing the hazards. The other hazard is related to undesirable events which can occur during the project's life cycle and directly influence the health and safety of industrial property such as fire, explosion, and collision. The CFD tool is not a general interface tool; however, it can simulate and visualize such engineering phenomena with a different level of detail, and it allows cost-effective and time-saving designs by utilizing the results obtained through CFD analyses.

Therefore, herein we propose integrating the BIM data platform and CFD design packages for a more comprehensive hazard analysis as shown in Figure 6, which describes the schematic diagram consisting of three sections: hazard conceptual design, hazard analysis, and mitigation and application.

In the proposed process, each stage of the integrative perspective becomes an essential part to offer the parameterized BIM database for the use of architectural, structural, and other functionality concerns. The relevant hazard design factors and requirements should be considered, and complementary cooperation is made at the early stages, such as at the conceptual and preliminary evaluation stages. In the conceptual design of industrial facilities having potential hazard issues, it is required that the experts in different fields should conduct tasks for preliminary hazard evaluation at several perspectives such as international rule checking, and environmental factors' identification associated with possible undesired events. For the hazard analysis part, a series of parametric modeling processes are required to express computationally hazard situations considering geometrical characteristics, material properties, and structural components. A BIM database is supposed to offer general interfaces for a different level of detail, and different analysis purposes, to easily extract necessary data, and thus efficiently gains feedback, and the CFD tool provides the insights and reasonable engineering basis to help engineers optimize their designs against a hazard situation. With such database and design technologies, particular hazard events could be modeled parametrically with specific information of the target facility, and hazard frequency and corresponding consequences' data are used to calculate the explosion risk rating. Lastly, hazard acceptance criteria are established based on hazard quantification results, and then preventive measures would be carried out if necessary. The system must be redesigned, or a hazard control option must be adopted, to mitigate the damage against corresponding issues. Every consequential change would be recorded by the well-dependency relationships between geometrical components and functionality subjects of the BIM database to prevent future hazard events.

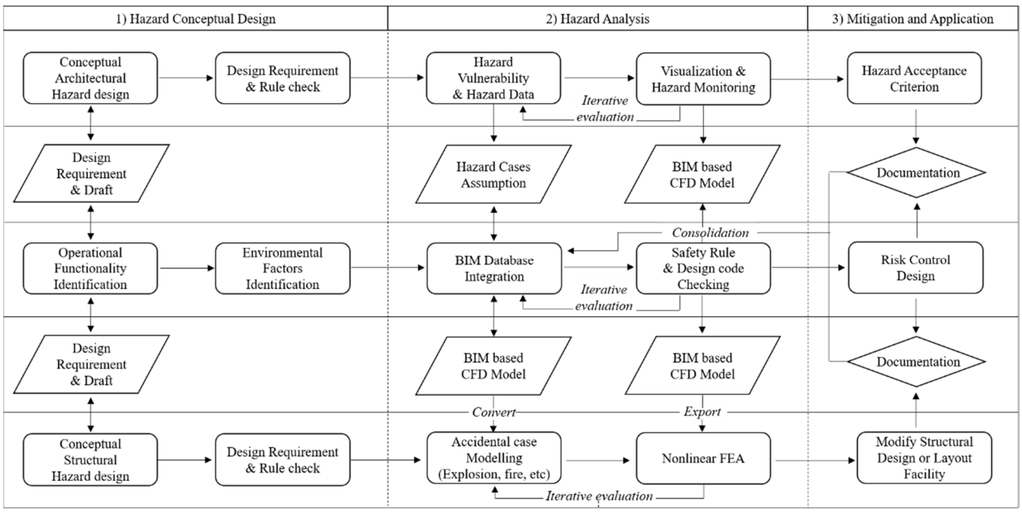


Figure 6. The flowchart for integrating the BIM data platform and CFD design packages for a comprehensive hazard analysis.

5.2. Framework of a Proposed Comprehensive Hazard Analysis Using BIM and CFD

The proposed semi-quantitative hazard analysis using BIM and CFD tools follows the framework for information modeling dividing into three stages as described in Figure 7. The detailed tasks for each phase are as follows.

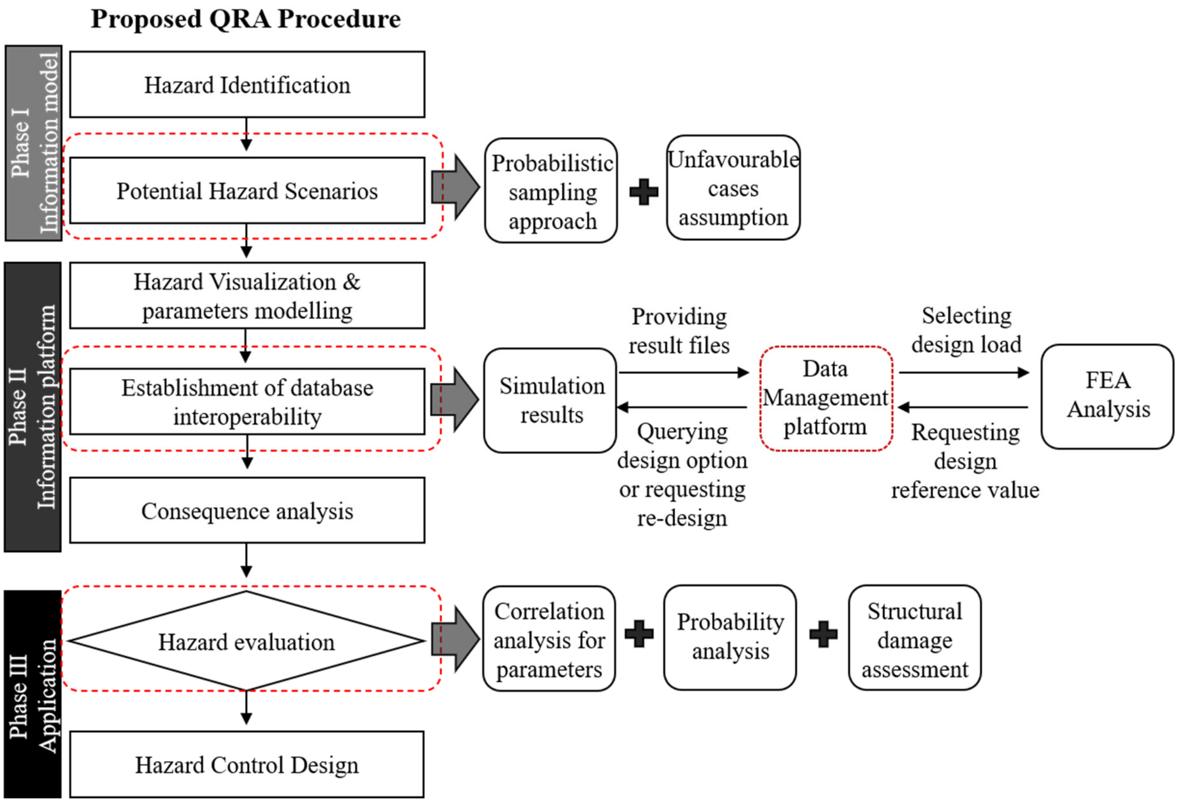


Figure 7. The framework of the proposed hazard assessment using BIM and CFD integration.

5.2.1. Phase I: Hazard Information Model

As the input data preparation stage, Phase I, the hazard information model, consists of two steps: hazard identification and scenario selection. At first, hazard identification provides important data associated with undesirable events, which help to define the relevant parameters to assume hazard scenarios. A variety of hazards and uncertainties existed in the project are identified in this stage. A BIM database technology that could be used to extract intelligently valuable expertise and information based on specific requirements naturally facilitate the early hazard identification and mitigation since the information and experience obtained from previous accidents offer a better perception not to repeat similar mistakes. For the hazard scenario selection, a range of cases should be considered to represent most features of reality. Therefore, it is required to select hazard scenarios reasonably. For example, the severity of explosion accidents is dependent on the environmental condition, operational condition, material composition, structure type, layout, etc. Most input data can be acquired by collating and referring information preserved in previous projects, while reasonable assumption and the idealization process are required to determine environmental parameters having strong inherent randomness, such as wind or leak profiles. That means a combination of several mathematical equations are required to process them, and the CFD tool can offer the solution for that. For example, Ref. [136] used the stochastic sampling method in explosion scenario identification to consider different affecting parameters such as wind direction, wind speed, leak rate, leak duration, leak direction, and leak position, and then analyzed the hazard distribution and summarized the main hazard factors that led to greater damage to the facility. It allows a better understanding of the mechanism of an accident and a better insight of how to assume such random variables in a future hazard analysis.

5.2.2. Phase II: Hazard Information Platform

Phase II, the risk information platform part, comprises three steps, and mainly focuses on the establishment of the hazard information platform by combining the hazard visualization through the detailed geometric model and consequences of hazard events. The application of virtual reality (VR) to hazard visualization is one of the major interests in this stage. It can provide a virtual and interactive computer environment for users to become conscious of defined hazard factors, so that they can formalize reduction strategies and measures of potential hazards.

A CFD analysis can model hazard phenomena in complicated flow geometries by computing the numerical solutions using relevant governing equations for the phenomenon. To solve the problem involving fluid flows, the discretization process of several coupled algebraic equations is required, and then such calculations are applied to each subdomain, and then the outputs obtained by the CFD model numerically indicate a great deal of information about the phenomenon. Therefore, the level of hazard is perceptibly defined, and VR simulation provided with CFD numerical results can increase the sensory level with exactly quantified hazard factors.

The consequence of a hazardous event is dependent on a lot of variables, but the CFD simulation consolidating BIM models as the object domain can reflect such a complexity with more realistic and accurate input data. In practice, CFD have been encapsulated as packages or compatible applications to integrate with current BIM visualization tools. They can analyze and provide rapid analysis results through certain model simplification processes with a standardized data format, such as gbXML, and so forth.

5.2.3. Phase III: Application

As an application of hazard information platform, Phase III mainly considers the method for mitigation of facility damage by the hazard elements. The hazard acceptance criteria can be used for taking preventive action against potential accidents. If the predicted hazard level exceeds an acceptable range, the modification of structural design or layout facility is required.

6. Conclusions

BIM–CFD integration and its applications represent an active research topic for the future development of AEC industries, especially in the field of the efficient energy environment. A growing number of studies have shown that BIM–CFD consolidation has promising prospects in numerous applications. This paper has reviewed the recent literature on such integrated technologies and its applications in several sectors. Through the literature study, this work has statistically summarized the existing state of affairs and practical applications of BIM–CFD integration. The applications of BIM–CFD integration have been discussed from four sectors: architectural design and building management, energy, HVAC system design, and facility safety management. The impacts and potential trends of the BIM–CFD integrated application in each field have been identified through a comprehensive investigation regarding architectural design practice and the current status of such a consolidation, and the general flow of current building design processes has been established. In addition, it was revealed that the conventional architectural design of the mentioned domains lacks the flexibility in requesting the new concept or re-design parameters without the integrated BIM–CFD design concept, and also interactive and cooperative abilities at early conceptual design stages.

The advantages of the use of the integrated BIM–CFD analysis are two-fold. For one, it is especially beneficial when simulating complex and challenging buildings, since realistic and accurate input data are readily available for CFD simulations. In turn, the CFD analysis results, in terms of air quality, energy consumption, thermal and ventilation performance, etc., can further enrich the BIM, providing informative support to a wide range of decision making. Yet, current efforts of integrating BIM and CFD mainly focus on the design stage, aiming to achieve a more sustainable and comfortable built environment.

For this reason, a future study is proposed to expand the application of integrated BIM and CFD. The proposed research is a quantitative risk assessment using BIM and CFD integrated technologies, which allows a more effective collaboration between engineers and designers at different stages of a construction project, and a more precise analysis for quantifying risks in the AEC industry. Herein, one of the critical challenges in implementing BIM–CFD integrated risk assessment is to ensure well-defined process models and practical strategies for the integration of risk information, and engineers and designers should work closely throughout the entire design process, and fully understand input parameters and corresponding simulation results to reach a more effective risk control design environment.

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List of Abbreviations

Abbreviation	Definition
BIM	Building Information Modeling
CFD	Computational Fluid Dynamics
AEC	Architecture, Engineering and Construction
IPD	Integrated Project Delivery
IoT	Internet of Things
GIS	Geographical Information Systems
HVAC	Heating Ventilation and Air Conditioning
PPD	Predicted Percentage of Dissatisfied
PMV	Predicted Mean Vote
ATF	Active Transparent Façade
PCM	Phase Change Materials

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