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Computational Fluid Dynamics of Wind Flow and Air Pollution Modelling: A Review on 3D Building Model Standards

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Computational Fluid Dynamics of Wind Flow and Air Pollution Modelling: A Review on 3D Building Model Standards

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Abstract. Computational Fluid Dynamics (CFD) simulations are used to monitor air pollution events supported by real-world conditions digitally. Besides, wind flow that has a close relationship with air pollutants dispersion also can be visualized by using CFD simulation. The presence of a building, especially in terms of the building's geometry, impacts the air pollution dispersion and wind flow that occur around a building or in a specific research area. As there is an involvement of building models in the simulation, some of the standards for the building modelling: Computer-Aided Design (CAD), City Geographic Markup Language (CityGML), and Building Information Modelling (BIM), are being utilized in this type of study. Many types of research have been conducted to study the pollutants and wind flow using the CFD technique of these three standards. Hence, this review paper is used to presents several pieces of research on this related topic. Through this review paper, some of the drawbacks of the study were identified, such as the detailing of the building's geometry and the compatibility of each standard to be implemented in the CFD simulation.

1. Introduction

Air quality modelling is a widely used technique to visualise the impact of air pollutants in the vicinity of the study area. Many contaminants can exist in the model, and some of them are sulphur dioxide, nitrogen oxide, and carbon monoxide [1]. Computational Fluid Dynamics (CFD) simulation is one of the most well-known ways for presenting the level of air pollution. Aside from air pollution, the CFD technique can also be used to simulate wind flow. This simulation can be performed digitally by utilising free and even paid software, namely Autodesk CFD, Ansys Software, and OpenFOAM [2]–[5]. This software can support performing many different fluid simulations and can be used for air pollutants simulation and wind flow prediction. Apart from the pollutant concentration value, the key parameters included in a pollutant simulation are wind velocity, temperature, and pressure. They can help better predict the flow of the pollutants as they reflect the actual conditions in the study area.

There is a need to include building models within the research area or the tree and other city furniture to make this obstruction give the actual effect of pollutants and wind flow to get a realistic depiction of the study area in this CFD environment. Hence, for the instance, in urban study area, the building models are the essential obstacle to include. This is owing to the fact that buildings make up the majority of the urban area, and they are the primary factor that can influence the flow of pollutants [6] in this type of research area. So, as to include building models in the simulation, many standards of building modelling already exist which can be chosen to be implemented, such as Computer-Aided Design (CAD), City Geographic Markup Language (CityGML), and Building Information Modelling (BIM). These standards are commonly used in different fields such as architecture, 3D Geographic Information System (GIS), and architecture, engineering and construction (AEC) respectively.

Numerous researchers have attempted on building modelling topic. Among them are three-dimensional (3D) modelling of buildings to determine the effects of urban heat islands [7], sensor placement for smart city applications [8], [9], heritage building modelling [10], and disaster management [11]. Apart from modelling the building itself, analytical studies on the modelling of building are conducted, including the use of efficient structural data [12], [13], 3D spatial queries [14], [15], and the combination of 3D building modelling data formats [16]. This demonstrates the versatility of modelling this structure in a 3D environment. The availability of a wide range of tools and data formats makes the process of constructing the model more straightforward, and integrations are seen conceivable.

CAD, widely known as Computer-Aided Design, is simply a design generated using a computer. AutoCAD is the most frequent software for creating this type of model. CAD places a greater emphasis on the design itself [17]. For instance, as in the scope of generating a building in a study area, a building model will be an example. Building in CAD standard focuses on design elements such as walls, doors, roofs, and a variety of other surfaces without embedding surface information. A good and high-quality model design can be obtained from this CAD standards model, but not the building information.

Furthermore, another standard that can be used in modelling building is the CityGML standard where it falls within the 3D GIS field. This standard is a worldwide standard utilized in modelling city building [18]. This ability can also be implemented in noise mapping [19], flooding mapping [20], and many more applications. This standard offers the knowledge on differentiating the complexity of building to be modelled, represented by the term Level of Detail (LoD): LoD0, LoD1, LoD2, LoD3 and LoD4 [21]. Despite differentiating the model, all the LoD include the same building information. The similarity comes from the specific surface layer name attached to the building model.

Besides, another standard is often found in the study of building modelling, which is the BIM standard. BIM standard, commonly related to the architecture, engineering and construction (AEC) field [22]. This is because this standard can provide complex building information not only on the generated building model but also on cost, schedule, and other information [23]. Information on building model existed in the BIM environment is too rich compared to CityGML and CAD environment. However, the detailed information is based on the level of development (LoD) in LoD100, LoD200, LoD300, LoD400 and LoD500 [24].

As in this study, three sections are presented: Section 2, Section 3 and Section 4. Section 2 is on the methodology involved while reviewing all the related papers on CFD simulation start from studying the paper until the process of analysing it. Besides, a critical review of the standard of building models embedded in the CFD simulation is described in the third section. Then, the final section, Section 4, concludes the overall idea of the review presented.

2. Methodology

This section describes the methodology used to review articles on CFD air pollution simulation and wind flow in a specific research area utilising building models created using three different standards: CAD, CityGML, and BIM. The whole methodology is divided into four phases, identification phase, screening phase, eligibility phase, and final selection phase (Figure 1).

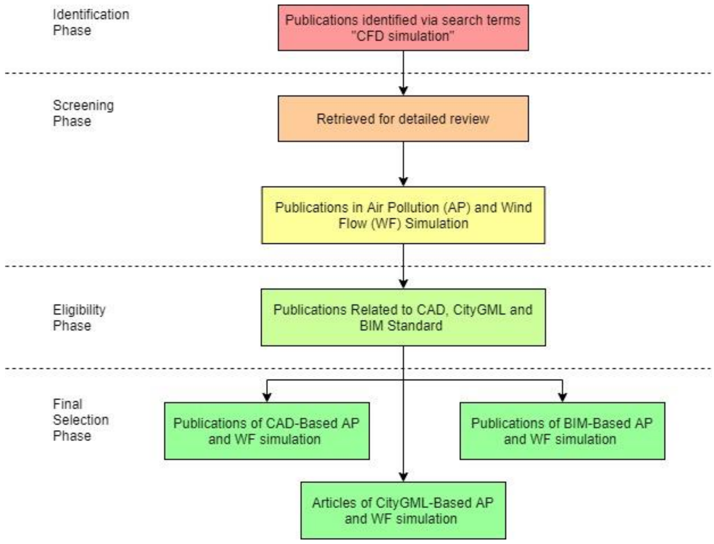

Figure 1. Flowchart of the reviewing process involves CFD related-building modelling standards, CAD, CityGML, and BIM with air pollution modelling and wind flow.

2.1. Identification phase
This first phase involves the collection of all existing publications on CFD simulation topics from the early 1970s from journal databases with the use of "CFD simulation" as the search term. The publications include the paper or articles from books, reports, conference papers, and journals. As CFD simulation is associated with any fluid flow, this application is widely used in many different fields, which are aerodynamics [25], heating, ventilation and air conditioning (HVAC)[26], heat transfer [27], electronic cooling [28], pollutants simulation [29] and many more.

2.2. Screening phase
During this phase, all the publications were reviewed and analyzed. Because of the plenty of publications on this related topic, only the publications on air pollutants and wind flow simulation were further processed. It is determined by studying the scope of the study presented in each paper, and from that, information such as the parameters used in the CFD simulation is recorded. This is done to ease the process of selecting the related topics to be reviewed in this paper.

2.3. Eligibility phase
Also, another element that was taken into consideration is implementation or utilization of a building model throughout the study of air pollutants dispersion and wind flow projection. This information is extracted from the selected papers by determining the building model and its standard implemented in the study. All the included studies integrated the CFD simulation of air pollutants and wind flow with the building model of selected standard. The building standards that involved are the model in CAD, CityGML, and BIM modelling standard. All these three are chosen to be included in this review because they are the main standards that are commonly being used in the building modelling field, in which CAD is the most popular standard in CFD simulation, CityGML is used as to represent a city modelling with well-documented standard, and BIM is the detail building information that can help in providing more details on the surface and building structures.

2.4. Final selection phase
For the final phase, the chosen publications were separated by following the building standard of the generated building model in the published study: BIM-based simulation, CityGML-based simulation,

and BIM-based simulation. After all of this has been done, the documentation of the selected publications was performed.

3. Building modelling standard in CFD simulation

The review is divided into the following subsections in this section. The first is the building modelling standard of Computer Aided-Design (CAD), the commonly used standard. The second subsection discusses the city building model standard, namely City Geographic Markup Language (CityGML). The final one encompasses the building modelling standards used of Building Information Modelling (BIM), which has detail building information.

3.1. Computer-Aided Design (CAD)

In the early 2000s, Ryu [30] performed a CFD simulation study that encapsulated the topic of determining the best simulation technique for airflow and dispersion around the building by differentiating the simulation results from two cases, including excluding viscous fluxes. An L-shaped building model of CAD standard is used to perform this study. From the result, it shows that simulation with the inclusion of viscous fluxes yield a better and accurate result.

CFD simulation of the wind flow is also performed to predict the wind environment for high and low rise building areas and compare the results with the wind tunnel experiment [31]. This simulation process in the two types of building complexes region is performed by using the building models in the CAD standard. This model later undergoes the mesh generation process before progressing to the simulation process. This study shows the nonuniform agreement of the predicted simulation result with the experimental study result. This is because the CAD model used is not entirely the same as the actual building model. Apart from that, the wind simulation by using CFD technique also can be utilized in the livestock building environment [32]. It is conducted to assess the effectiveness of the air ventilation inside the 3D CAD design building of different wind inlets and different wind indices. Through the study, the wind that blow normal to the building support the best ventilation process inside the building.

As studied by Panagopoulos et al. [33], the CFD simulation is performed to study indoor air pollution instead of wind simulation. It covers the indoor condition of a building. Specifically, it is an apartment that involves the kitchen area and a living room where the main pollutants or contaminants included in the research are Volatile Organic Compounds (VOC) formaldehyde. To model the building model of the apartment, CAD standard is used. However, through the whole research, there is no specific format of the CAD standard mentioned for the reader to know how the structure of the building is suitable to be implemented in the simulation process.

Besides, from the study conducted by Triscone et al. [34], the main objective to run the CFD simulation is to predict the air pollution in a neighborhood (Figure 2) experimentally and digitally where it is associated with outdoor air pollution. Pollutants such as Particulate Matter (PM_{10}), ozone (0_3), and nitrogen dioxide (NO_2) are involved in the simulation process. As the study is performed in the neighborhood area, then there is a use of a 3D building model. This model is produced in the form of CAD format for experimental and digital simulation. One method to obtain the building data is by flying the unmanned aerial vehicle (UAV) in the study area. The use of CAD can somehow ease the simulation process, especially in the digital way of performing simulation. Still, the drawback from the model is that there is no detailed building design embedded, such as the existence of a balcony that can manipulate the flow of pollutants.

Figure 2. 3D Model of neighborhood area of Paquis [34].

Chitaru et al. [35] presented a study of indoor air pollution that utilizes the classroom as the study area. The classroom was set as a boundary for experimenting on air ventilation. Also included is the pollutant effect from a gas such as carbon dioxide (CO_2). This study was performed to know the condition inside the classroom as the low quality of air ventilation and the presence of pollutants can impact student absenteeism and performance. To study air ventilation, the researchers had generated a CAD model of the building. The model in a 3D environment was extruded from a 2D model of the classroom. Additional detail was added to the 3D model, such as windows and doors elements, to increase the usability of the model. Hence, the pollutant level was determined by providing the 3D model and the related information for simulation purposes. Nonetheless, the opening of the door without closing it does not include in the study where only the opening of windows is considered although it has been modelled.

Furthermore, Jiang et al. [29] investigated the air pollutants dispersion in a residential area. The pollutants dispersion of gaseous is highly harmful to human health. When exposed to humans in an uncontrolled amount, it will introduce a health problem: particulate matter (PM2.5) and carbon monoxide (CO) were analyzed using CFD simulation. The building model in the residential area, pollutants information, wind velocity, and some other important input data for the simulation were embedded in the process of performing the CFD simulation to represent the real condition. Model of the building block of different morphology in the CAD model (Figure 3) was utilized to best predict the best and suitable design for a better air pollutants dispersion in the study area. Although the details such as Building Density (BD), Floor Area Ratio (FAR), Average Building Height (AH), Space Openness (SO), Standard Deviation of Building Height (SDH), Mean Building Volume (MBV), and Degree of Enclosure (DE) were included, however, the begin with, the detail building design by following a well-documented standard of building modelling can support in providing a more accurate building morphology.

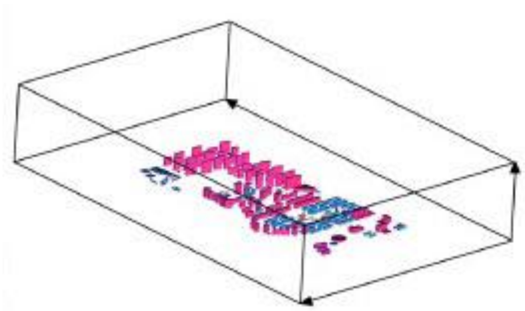

Figure 3. CAD model within the domain of CFD environment [29].

3.2. City Geographic Markup Language (CityGML)

Early research by Pontiggia et al. [36] employed CFD simulation to examine gas dispersion in an urban area. To represent the city, a set of building models in a so-called 3D city model, known as CityGML, was used. The model is incorporated in the study because of the existence of the building geometry, or to be more precise, the complex building model in the urban environment contributes to the manipulation of gas dispersion in the ambient air. Also, this 3D city model can represent a complete reconstruction of the urban area. However, the LoD of the model used is the one with LoD1 detailing only. This is because the author wanted to make sure that the intricate design of the building model is compatible with the simulation runtime and associated CPU performance. The result of this study is the gas dispersion, in which in this study the ammonia gas (NH3) was used, which can be portrayed supported by the use of the building model in the integration with the CFD simulation. Despite the great ability to model gas dispersion by implementing the CityGML-based building model, the more detailed building model is suggested as the more detailed LoD representing the more detailed building design.

Piepereit et al. [37] have performed a study on wind simulation using CFD simulation. This simulation was supported by the 3D building model of the CityGML standard in order to visualize the wind flow surrounds a study area. The model in CityGML format was used at the starting point, but it is then converted into a CAD environment using a newly proposed algorithm, namely a sweep-plane algorithm. This algorithm enables the data generated in CityGML to be utilized in the wind simulation by simplifying the geometry of the model. Figure 4 shows the pseudo-code of the algorithm that runs on the model of CityGML. As the final result of this study, the wind flow surrounds the building model that has undergone a sweep-plane algorithm were simulated using ANSYS software (Figure 5). Further study on the CityGML standard structure should be done to avoid it from being converted to CAD standards for simulation purposes.

Algorithm : Sweep-Plane Algorithm

Input : Building with Faces F and Edges E
Output : Modified Building
while $e \in E \mid lenght(e) < \epsilon$ **do**
  $F' = \{f \in F \mid u, v \in e, u \in f, v \notin f,$
   $isSweepPossible(f, dist(f, e))\}$
  $f' \leftarrow any(F')$
  $\sigma(f') \leftarrow Sweep(f', dist(f', e))$
  $f^* \leftarrow MergeFaces(\sigma(f'))$
  $DeSweep(f^*, dist(\Delta V))$
end

Figure 4. Pseudo-code of sweep-plane algorithm [37].

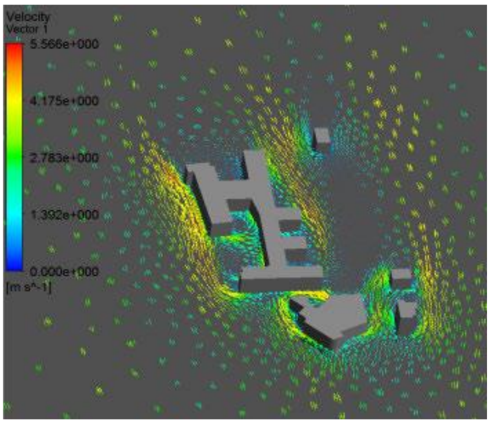

Figure 5. CFD simulation of wind performance associated with 3D building model and wind information [37].

The building standard of CityGML is embedded in the study of visualizing the wind fields in the urban area [38]. This research highlights the use of the city building standard, which is the CityGML standard, in enhancing the CFD simulation process. It is done by utilizing the building model of LoD1 (Figure 6) and an additional vegetation model in the study area to increase the accuracy of the simulation prediction. Later, after several processes underwent, such as optimization of the model's geometry, integration of vegetation and terrain model, the whole data are being exported into CFD simulation to visualize the wind flow. The final part, this research enable the web visualization of the generated simulation of the wind flow using the 3D Geo-data Portal. This study portrays thorough documentation of the use of the CityGML model in the CFD field, and it allows the layman to visualize the simulation by only using a common web browser. Consequently, through exporting the CityGML file into the simulation environment, there is a need to convert it to a CAD file first. This shows that there is still room for improvement in this aspect to allow the CityGML file to be imported directly into the CFD environment.

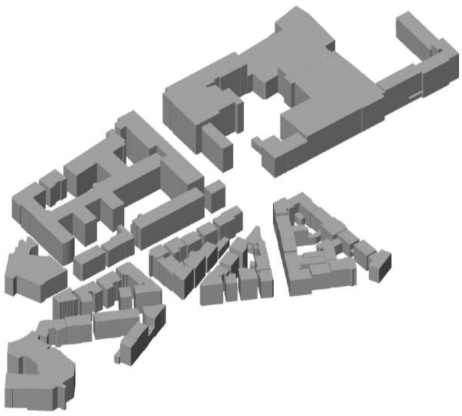

Figure 6. CityGML-based building model [38].

3.3. Building Information Modelling (BIM)

In this section, more study has been conducted on wind flow compared to air pollutants dispersion. As researched by Lee and Song [39], CFD simulation is used to evaluate the wind environment throughout the research area, which is located in an urban area. The building model was included to support the visualization of wind flow to study the wind condition in that urban area. The model is generated based on BIM standards. There are several different buildings types involved in this study to enable selecting the most suitable building design to be built. Apart from focusing solely on the building model, the author also considers the appropriate mesh generation for the model to be included in the simulation and the CPU time required to process the simulation. Although this study can show the best value of mesh generation on the BIM-based building model, for a real-world condition, the building detail should be more precise to get a better wind simulation.

Wind performance evaluation surrounding a building to be designed proposed by Kwong et al. [40]. To strengthen the idea of generating the building, the collaboration of knowledge between structural engineering and architecture field were combined to enable for the production of building that following the standard of building the ability to withstand the wind condition and its aesthetic value. Different designs of 3D models (Figure 7) of high-rise buildings were introduced to study the effect of the wind flow on the building. The model is generated based on the BIM standard of building modelling of the early design phase. According to the research, the best way to overcome the wind pressure on the building is to use façade layering, planar railing elements, and rectangular element cross-sections. However, as the building progresses until the as-built phase, the model will happen to include more details on the design, where it can impact the wind flow. Hence, a new in-depth study will have to be conducted to cater to the newly implemented details.

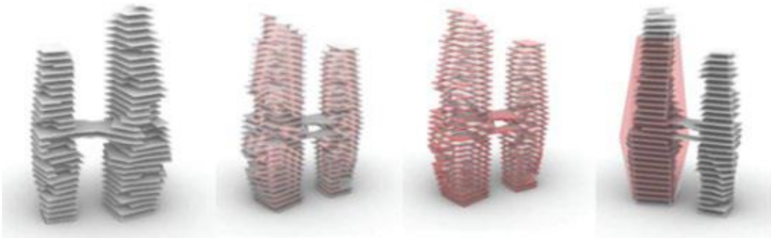

Figure 7. Different design of building facade involved in wind performance evaluation [40].

By referring to a paper by Zorzi [41], air ventilation in a hospital's space was examined to support in the reduction of the impact of the SARS-CoV-2 virus to be suspended in the air. It is important. After all, the suspended virus may increase in Covid-19 cases because the people who walked past through the space inhale the contaminated air. The simulation of the air (Figure 8) was presented using the CFD simulation of Autodesk CFD software. To represent the space, the BIM model was integrated into the simulation, where this BIM model was generated in Autodesk Revit software. From the study, the suitable ventilation pattern was determined, in which this pattern allows for good air ventilation that hinders the suspension of the harmful virus in the air. Nevertheless, the information of the SARS-CoV-2 virus needs to be included as it also has its own level of diffusivity without only focusing on the wind flow in the well-represented 3D space model.

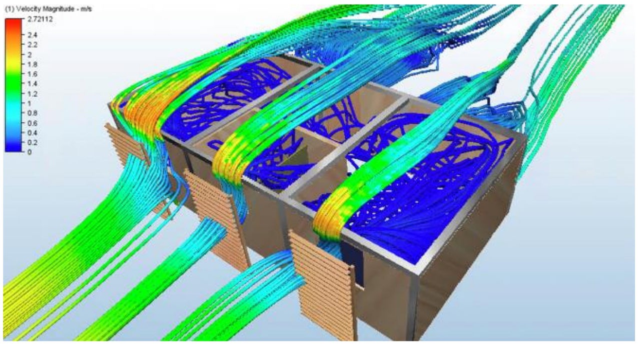

Figure 8. CFD Simulation of wind with respect to the hospital's space [41].

Meanwhile, Lee et al. [23] studied the CFD simulation method by utilizing the BIM-based building model. The research begins with data extraction of a BIM model from an IFC file format, then moves on to simplifying the geometry of the created building model, grid optimization, and attribute data matching from the IFC data. The final step is to export a case folder for the OpenFOAM CFD software. In addition, a validation process of the accuracy of simulation result and the grid model was performed to make sure that this newly proposed method is acceptable by using another CFD software, ANSYS software, and conducting a case study. The IFC file's geometry and attribute data can be integrated into the CFD simulation, as in the OpenFOAM simulation of a BIM-based building model. Consequently, before the geometry data can be used in the simulation, it must first be turned into a 3D CAD model. Hence, adopting the BIM model is still a disadvantage because it must be converted into a different format.

4. Discussion

As presented in Section 3, many types of CFD simulation studies exist, which are related to the wind environment and air pollution study. The CFD simulation study can be found from the research as early as in the middle 90s; however, with the development of technology, the study on CFD simulation began to develop in the 2000s and is more stable to be conducted than before [42]. From the perspective of wind CFD and air pollution CFD study, it shows that there is an integration between the simulation environment with the fluid flow movement from the scope of wind and air pollution. Aside from that, to show the interaction with the building model, there is a need for the building model to be included in the simulation process. Some modeling standards are used to model the building, such as CAD, CityGML, and BIM.

Many CAD-CFD simulation studies have been conducted as early as the 2000s, but the emergence of CityGML and BIM standards in the CFD simulation is quite late compared to the CAD standard. The use of CAD modelling usually does not follow any specific rule of modelling, as this standard is commonly used because of its compatibility with the CFD software to perform the simulation [43], [44]. However, because of no specific specification to be followed, such as building information and building detailing rules, the geometry generated, mainly the building model, has not had enough capability to represent the real-world building representation or building model to be developed [30], [34]. This is important because when there is an involvement of the actual study area, the excellent and complete representation of the building model can better show the manipulation of fluid flow throughout the whole study area [6].

Instead of the CAD modelling, there are CityGML and BIM standard modelling. These two standards lead the building modelling field because they are a well-known standard in 3D building modelling field and can be found in many types of research [18], [45]. One of the criteria supporting the emergence of these standards in the CFD field is these two standards' ability to differentiate the building detailing. It is used to represent the building model with respect to different levels of detailing, and the main thing is that it is a following a certified standard. With the different detailing levels presented in CityGML and BIM standards, researchers have the option to choose the best-detailing building representation to accurately represent the real-world building model, especially for the study in a specific study area.

In the scope of 3D building modelling, BIM standard has an outstanding portrayal of building information with dense information on the building, whether on the structure of the building, size, thickness of the wall and even the construction cost and many more information. Also, with its building model detailing in the concept of level of development, where the development process differentiates it from the construction to the as-built design. However, although with excellent building information provided in the BIM environment, this is somehow is not very useful as the CFD simulation is focusing more on the geometry of the building to be included in the simulation [46]. This is because there is one process called meshed of geometry in the CFD environment. This process determines the accuracy of the final result of the simulation. This shows that mesh is only performed on the geometry of the building itself, not with the other parameters. Hence, it is good to have very detailed building information to add the output of the simulation with excellent details of the building model. But, to produce an optimum geometry representation, a less complicated building modelling with lesser information can be used, which is the modelling in the CityGML standard.

This CityGML standard can support the process of presenting the best geometry in the CFD environment. This is due to its building detailing concept that provides the representation of building from the simplest form, which is only the building block, until the complex structure, which somehow represents the real-world building representation [47]. The best building model in the suitable detailing can be chosen from all the LoDs for the purpose of CFD simulation. This can be significantly utilized in the simulation because from the perspective of LoD in CityGML standard, the geometry of the building model is the primary element to be considered, in which this geometry is to be implemented in the CFD simulation environment. Specifically for the 3D city modelling, CityGML is the most suitable standard to represent the 3D building model in the city area [48]. To perform a CFD simulation of wind or air pollution in an urban area, CityGML is recommended because of its ability to represent a larger spatial extend and provide good and enough information on building modelling.

Nonetheless, CityGML and BIM modelling is not compatible to directly integrate with the CFD environment, so there is a need to convert into CAD modelling [23], [37]. But, by performing this, although it is in the CAD environment, the building detailing is already following the building modelling standard and, because of the present CFD software, only supports the CAD building standard [49]. However, with the excellent development of technology and the intensive study on 3D city modelling, a new platform to enable the integration of CityGML and even BIM modelling directly with the CFD environment is suggested. This is because many mega and big cities such as Singapore [50] and Netherland [51] already have their 3D city modelling in CityGML standard, so to support sustainable development, air pollution and wind simulation study are some of the events that need to be monitored regularly. Thus, the direct integration of the existing building model and CFD simulation environment can enhance and ease the simulation process. However, with the excellent development of technology and the intensive study on 3D city modelling, a new platform to enable the integration of CityGML and even BIM modelling directly with the CFD environment is suggested.

5. Conclusion

This paper reviews the building modelling standards used in the CFD simulation of air pollutants and wind flow: CAD, CityGML, and BIM. These three modelling techniques enable the CFD simulation to incorporate a building model or the whole research area of a building model. This model can be combined with the CFD environment since the building's presence influences the flow of wind and pollutants. Hence, this parameter can help in better portraying the real-world condition in the research area. From the review, there are several ways of performing pollutants and wind dispersion simulation concerning the chosen building standard. Each research somehow has its drawback, but if the comparison between the use of CAD, CityGML, and BIM-based building model in CFD simulation is made, the CAD model shows a good fundamental as when the researchers want to use CityGML and BIM, there is still a need for conversion into CAD format. Therefore, more research has to be performed to enable and enhance the use of CityGML and BIM building models directly into the simulation environment.

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