Applications of Building Information Modeling (BIM) in Disaster Resilience: Present Status and Future Trends

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Abstract –

Natural disasters such as bushfires, wildfires, hurricanes, earthquakes, and floods cause significant socioeconomic losses with associated damages to communities. From 2005 to 2014, the worldwide damage caused by disasters has been more than US$1.4 trillion, with 0.7 million deaths and 1.7 billion people affected. In order to reduce the negative impacts of disasters and strengthening communities, the disaster resilience topic has been receiving increased attention to maximize the ability of communities to adapt and recover fast. Disaster resilience can benefit from Building information modeling (BIM) as an effective tool to facilitate informed decision-making. This article provides a comprehensive review of the existing literature on BIM applications in disaster resilience. Past research studies are categorized by the year of publications, type of disasters (fire, earthquake, flood), phase of the disaster (mitigation, preparedness, response, recovery), and target groups (buildings, infrastructures). The paper aims to provide a holistic review of research trends and patterns, emerging technologies, benefits, challenges and limitations, and research gaps.

Keywords –

BIM; Building information modeling; Bushfire; Disaster; Earthquake; Evacuation; Fire; Flood; Resilience; Review

1 Introduction

Based on the report of the United Nations Office for Disaster Risk Reduction (UNDRR), the number of disasters associated with natural hazards has increased over the past two decades. Consequently, communities should be prepared to recover from the impacts of disasters. A disaster-resilient community should withstand a natural hazard with a tolerable level of losses and adopts mitigation actions consistent with the desired level of protection [1]. The number of scientific research studies on disaster resilience has increased dramatically in recent years as shown in Figure 1.

Integration of disaster resilience and Building information modeling (BIM) provides an effective tool to help decision-makers visualize what is to happen in a simulated environment [2]. Similar to research on disaster resilience, the number of studies on BIM has increased over the past 20 years as presented in Figure 1. Although many BIM applications have been explored in the literature, applications for disaster resilience is scarce.

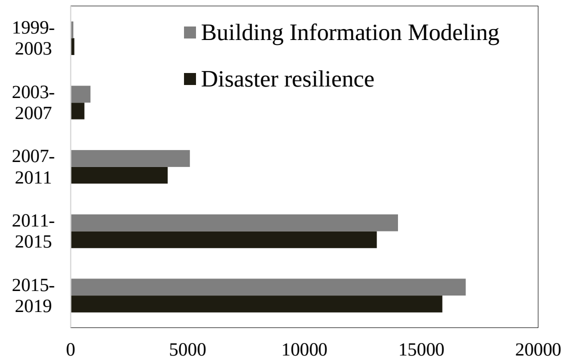

Figure 1. Number of publications on “Disaster resilience” and “Building Information modeling” in Google Scholar during the past 20

This research carries out a systematic review of the relevant literature with the following objectives: (1) classification of papers on BIM applications for disaster resilience; and (2) scoring the papers based on relevance; and (3) categorizing the selected papers based on the type and phase of disasters; and (4) identifying the research gaps in the literature, and outlining the potential future research directions.

Following the introduction, section 2 describes the research methods adopted in this paper. Section 3 provides an overview of the current literature on BIM applications for disaster resilience. The detailed BIM applications are categorized and described in Section 4. Section 5 outlines the identified research gaps and opportunities for future research. Finally, the conclusion is presented in Section 6.

2 Research methodology

The review method was informed by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [3]. In the first step, about 30 BIM review papers were assessed, and the papers on the disaster resilience area were shortlisted. In the second step, two search attempts were conducted to find relevant studies. The keywords of the first attempt comprised building information modeling, BIM, and resilience, which resulted in finding 63 papers. In the second attempt, keywords such as building information modeling, BIM, disaster, flood, hurricane, tornadoes, volcanic, wildfire, earthquake, tsunami, and storm were utilized, and 251 research studies were found. The studies found in the two attempts were merged and the duplicated papers removed. In the next step, the evaluation of article titles was conducted to find the most suitable papers. Consequently, the outcome contains 123 papers.

In order to select the most appropriate papers, a selection system was needed. The selection system of these papers considered four important paper quality indexes such as authors' expertise, paper citations, and journal quality. Indexes are described as below:

- **Authors' expertise:** The authors' expertise is a critical index for the quality of the paper. The h-index of authors can be a good measure in order to show their expertise.
- **Publication date:** new publications can demonstrate the trends of current research; thus, they are more interesting for researchers. The current paper reviews papers that have been published during 2007-2020.
- **Paper citations:** Number paper citations are a measure of validity. Papers published before 2018 without at least 10 citations were excluded from this review.
- **Paper type:** Only books and journal publications are considered in this review paper.

All 123 papers are evaluated based on the above indexes. Consequently, 42 papers are detected as the most relevant papers that should be reviewed in this paper. Using the abovementioned approach, a comprehensive analysis of the literature was conducted. The comprehensive literature review provides useful information about identified gaps and opportunities for future research. The process is demonstrated in Figure 2.

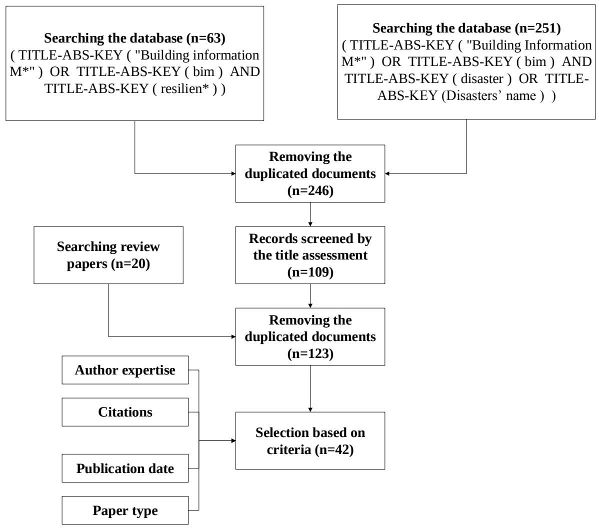

Figure 2. The process of the systematic review

3 Analysis of publications

The database of the nominated papers contains articles published from 2007 to 2020. However, about 39 percent of the selected papers are published after 2019. This means that the attention to the BIM applications for disaster resilience has been increased. Most of the selected papers has not been reviewed by the past review papers. Only 4 papers [4]–[6] among 44 papers have been reviewed by Tang et al. [7]. The selected papers have been published in 25 different journals. The journals with more than one included paper and their research impact are shown in Table 1. Based on the database of selected articles, an analysis was performed on the content of the article titles and abstracts to identify the most occurring topics. VOSviewer was utilized in this paper. Constructing and viewing bibliometric maps can be done by VOSviewer. The size of the label and the circle of an item is determined by the weight of the item. In addition, the distance between the two circles reveals the relatedness and similarity between them. The lighter colors show more recent papers as the graph guide. The output of VOSviewer is shown in Figure 3.

Table 1 Top journals in BIM applications for disaster resilience

No.	Journal name	No. of papers	CiteScore 2018
1	Automation in Construction	13	6.35
2	Advanced Engineering Informatics	5	5.72
3	Journal of Computing in Civil Engineering	4	2.55
4	Water (Switzerland)	2	2.66

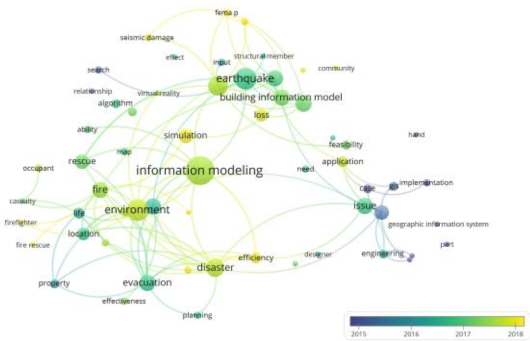

Figure 3. Main research areas in BIM applications for disaster resilience and its trends

4 Discussion

The database of the papers contains the most outstanding papers on BIM applications for disaster resilience. The BIM applications can be categorized based on the phase of the disaster. Four disaster phases (preparedness, mitigation, response, and recovery) are considered in this paper. Disaster preparedness is persuading organizations to realize the hazard that has to be faced. Loss reduction by identifying the risk assessment is disaster mitigation. Disaster response is associated with the post-disaster situation and it contains actions such as damage assessment and evacuation. Post-disaster activities that restore or improve the pre-disaster conditions can be defined as disaster recovery [8]. In addition to disaster phases, the selected papers analyzed the BIM applications based on disaster types. The database comprises the application of BIM for fire, earthquake, and flood.

4.1 Fire

Based on the publication date, it can be mentioned that the BIM application for fire response is the first BIM application for disaster resilience. Structural fires are common urban disasters. Traditionally, the 2-D maps guided people to find the exit routes in emergencies such as the fire in buildings. The outdated approach has a few critical limitations. For instance, it is possible that people cannot interpret 2-D maps correctly. The BIM applications for fire are generally related to preparedness, mitigation, and response phases.

4.1.1 Pre-disaster rescue route planning

BIM can be an appropriate tool for visualizing and providing insight. Pre-disaster rescue route planning concentrated on finding the shortest route. GIS historically utilized for finding the evacuation routes. However, in order to information transformation, Isikdag et al. [9] presented a combination of BIM and GIS to find the rescue routes. Li et al. [6] designed an algorithm for finding the location of trapped occupants at building fire emergency scenes based on BIM and GIS integration. A graphical interface for user interaction is provided by the model. Chi et al. [10] proposed that evacuation regulation can be done based on static rescue routes evaluation and BIM models. Designers can check their design by the proposed methodology, and revise it if it is mandatory. The distance of the exit routes is assumed as the longest possible distance.

4.1.2 Dynamic rescue route planning

Not only should the rescue route be short, but also it must be safe and obstacle-free. These rescue routes may be changed during the disasters based on the fire condition. Consequently, rescue routes should be determined dynamically. In most cases, firefighters lose a great amount of valuable time to get familiar with the site. BIM-based 3D model can help them to find invaluable information about the building easily. Shiau et al. [11] create a web-based fire control system based on BIM. The characteristics of the building material are accessible in the 3D map. A lot of fire detectors and monitors are available in the building, and their information is integrated by the 3D map. Firefighters could find the best relief program based on the material type around the fire location. Wang et al. [12] utilized BIM as a comprehensive building information model to provide real-time guidance for fire evacuation. The shortest evacuation routes generated by the A* search algorithm. The results of the path finding algorithm should be safe with no obstacles. Users can show the result of the path finding on their mobile devices using virtual reality. In addition, the developed methodology can propose a suitable path for disabled evacuees. Yoon et al. [5] presented a smartphone-based, in-building emergency response assistance system that can provide useful information about the location and physical status of victims. The location of the victims can be determined by Wi-Fi signals of the smartphone. The status of the victims is assessed by asking themselves or sensors in their phones.

Happening a disaster in a surrounding building may block a few entrances and exits and change the navigation routes. To remedy this problem, Tashakkori et al. [13] proposed a model that considers the information about the interiors and exteriors of the building in the fire management system. Chen et al. [14] integrated Internet of Things (IoT) technology and BIM in order to monitor the real-time situation during a fire disaster. The system controls the LED guide pointers to help evacuees find the best routes. Chen et al. [15] integrated network analysis with building information modeling (BIM) to help responders can find the rescue routes by using the developed graph. The route selection procedure is a function of distance, risk of the disaster, and people congestion in this study. Chou et al. [16] developed a framework of dynamic evacuation procedures for departments. The best fire rescue paths are calculated based on the shortest path algorithm. Bluetooth sensor outputs show the information of temperature and smoke of routes. The best routes are updated based on this information.

4.1.3 Evacuation route considering human behavior

The crowding effect should be considered in rescue route planning as well. For this goal, human behavior is required. Cheng et al. [17] considered the individual characteristics (e.g., confusion and nervousness in an emergency event) in the mobile guidance device of the proposed BIM-based model. Marzouk et al. [18] present a framework to help managers to plan for labor evacuation in construction sites. BIM and agent-based simulation are utilized in the mentioned framework. The Evacuation Simulation Model contains an agent-based simulation approach to simulate the labor evacuation considering labor behavior. Mirahadi et al. [19] developed a tool that is named EvacuSafe. EvacuSafe can be useful to increase the evacuation safety performance by considering fire risk and population crowd risk. It comprises an agent-based model to predict the behavior of the residents. Ma et al. [20] a fire emergency management system based on the BIM platform. The developed system can consider the behavior of evacuees during fire disasters. People can find optimal paths such as obstacle-free and minimum distance by using technologies. Then, they will select their way. The fire management system effectively manages fire disasters based on fire conditions and people's behavior.

4.2 Earthquake

Earthquake is the second disaster type which can be managed by BIM. Earthquakes are major threats to many societies across the world [21]. Early research studies tried to prove the applicability of BIM for enhancing the seismic resilience of buildings. A research study by Welch et al. [22] is devoted to investigating the possible BIM application in seismic resilience area. Welch et al. [22] argue that BIM application for earthquakes can be classified into 3 groups. First, BIM comprises detailed information about building for seismic risk assessments. Second, BIM can be combined with structural health monitoring to protect critical buildings such as hospitals. Third, BIM can pave the roads of information communication in the emergency shutdown in order to efficiently make decisions to identify, prioritize, and manage risks. In this paper, the research studies on BIM application for earthquakes are classified anticipating the as-damage BIM model, design guidance, search and rescue application, and fire due to the earthquake. Anticipating the as-damage BIM model, and design guidance belongs to the preparedness and mitigation phases. However, search and rescue applications, and fire due to the earthquake belong to the response phase.

4.2.1 Anticipating as-damaged BIM model and loss estimation

To calculate the building strength accurately and demonstrate the anticipated damages after earthquakes, Anil et al. [23] developed an as-damaged BIM model. This model contains strength analysis and visual assessment including structural analysis models, building geometry and specification, material properties, reinforcement information, and damage records. The earthquake damages are predicted based on FEMA 306 guideline. The approach to forecasting the as-damage BIM model of a building based on its as-built BIM model is described by Ma et al. [24]. In addition, Zeibak-Shini et al. [25] anticipated the as-damaged model by developing an algorithm to assess the location and damage of each component of reinforced concrete frames with masonry infill walls. Ma et al. [26] forecasted the damage sequence information of a building based on BIM. Zhang et al. [27] highlighted the fact that due to hidden structural elements, building deflection evaluation after earthquakes is difficult and cost-intensive. On the other hand, this task plays an important role in occupant safety and should be determined. Sensors are able to solve this problem and provide updated information about building deflection. The output of the sensors can be easily visualized for users by using BIM.

Xu et al. [28] developed a BIM-based seismic loss evaluation based on FEMA guidelines. Consequently, decision-makers are able to observe the distribution of damage and loss in a virtual walkthrough. Considering the fact that FEMA guidelines require detailed information to predict building damages. In addition, the building components in the BIM model may have various levels of development (LODs). Xu et al. [29] found that some components may not have enough detailed information for analysis based on FEMA guidelines. They developed a framework to estimate the seismic loss of a model with various-LOD BIM data considering uncertainties. Vitiello et al. [30] implemented a BIM model in order to determine the most cost-effective retrofit intervention that can be determined based on the seismic loss estimation of each intervention.

BIM can be used in the design procedure as well. Non-structural building elements play an important role in performance-based earthquake engineering. Perrone et al. [31] developed a tool for the seismic design of non-structural building elements based on BIM. It is shown that the BIM model information eases the seismic design procedure of sprinkler piping systems. Furthermore, the finite element analysis needs accurate geometric characteristics of building elements. This accurate information can get available by BIM. Ren et al. [32] introduced a framework that can conduct a finite element simulation for a building based on BIM.

4.2.2 Search and rescue application and post-disaster fire

Traditionally, rescuers should enter the damaged building to collect information. This task is dangerous and time-consuming. Bloch et al. [33] provided a BIM approach in order to help search and rescue teams after earthquakes. The interior of the damaged building is estimated using the as-built and as-damaged BIM model. The developed framework can accelerate the procedure and save the search and rescue teams. Xu et al. [34] taught inhabitants how to survive in earthquakes by visualizing non-structural damages. 3D information BIM model of the building is the basis of the structural analysis and Virtual Reality analysis.

Fire disasters are common after seismic disasters. In most modern buildings, fire sprinkler systems are installed in order to protect the building against fire. However, sprinkler systems may sustain damages due to earthquakes. The effect of the spread of the fire owing to sprinkler systems damages is studied by Xu et al. [35]. In addition, Lu et al. [36] developed a simulation framework of indoor post-earthquake fire based on BIM. In this study, the post-earthquake fire, building damages, fallen debris are estimated. Considering the damages and fire conditions, the rescue route can be determined in a virtual reality scenario. The results can be used as a training tool for building occupants.

4.3 Flood

The third frequent disaster type in BIM research studies is flood disasters. Due to climate change, the number of flood hazards has been increased recently. In addition, high settlement density highlighted the risk of economic losses due to floods. The BIM application for flood hazards are more recent and are mentioned in below. Most of BIM applications for flood hazards are related to preparedness, mitigation disaster phases.

4.3.1 Damage assessment

The flood damage assessment should be done for each building separately. This requirement needs detailed information about buildings. BIM model is able to satisfy this condition based on Amirebrahimi et al. [37]. Based on this study, the effect of the flood on the building can be calculated and visualized. Amirebrahimi et al. [38] completed the past study by integrating BIM and geographic information systems (GIS). Considering the fact that the most application of GIS is related to an outdoor and large-scale geographical feature, and the most application of BIM is associated with indoor objects, BIM and GIS integration is a proper combination for flood damage assessment. BIM is responsible for building information, and GIS is responsible for flood information. Lyu et al. [39] recommended that BIM and GIS integration can be a suitable tool for city managers in order to assess the flooding hazards.

BIM has been used to investigate the impact of a dam on the downstream by Rong et al. [40]. The dam discharge and flood routing are simulated by BIM. The downstream flood risk is evaluated by simulating the dam operation under different water levels. The treats due to the reservoir flood discharge for the building is analyzed. The results of a case study show that reservoir flood discharge is a treat for a city on the downstream. Moreover, the potential flooding hazards for coastal cities can be anticipated by BIM. Traditional approaches utilize 2D modeling for flood hazards. However, their results are not appropriate for vertical fluctuations. Rong et al. [41] integrated BIM and GIS to simulate the wave propagation more realistically based on high-resolution topography data. The proposed methodology can provide detailed information about flooding hazards such as flood extent, axial velocity, and vortex structures, etc.

4.3.2 Real-time monitoring

BIM is capable to use in real-time monitoring the flood hazards. Edmondson et al. [42] developed a BIM model that comprises smart sensors. The BIM model can predict floods by real-time monitoring and reporting of sewer asset performance. This approach can be used in order to evaluate the risk of inundation of metro systems due to flooding hazards. Lyu et al. [43] presented a framework that comprises GIS and remote sensing. In this research paper is recommended that the integration of GIS, Global Positioning System (GPS), and BIM can is a tool for visual management of 3D geographic spatial location information. Consequently, managers can monitor the risks of inundations in the metro tunnel dynamically.

In addition to real-time monitoring of the water level, BIM can be used in real-time monitoring of the water diversion projects to find the defections. Insufficient inspection and late problem detection may lead to disastrous results. Liu et al. [44] proposed a framework to optimize the inspection process. Unmanned aerial vehicle (UAV) and BIM integration are used in the proposed framework. The BIM model is dynamic and it comprises timely-updated safety information. The model is shown in the Web environment.

4.4 General : Post-disaster construction

Biagini et al. [45] proposed utilizing BIM for the restoration of historical buildings. The main concern for the restoration of historical buildings is an on-site intervention. In order to efficient on-site intervention, a complete information plan should be provided for executing the restoration plan. Tradition restoration methods provided 2D maps that generally comprise insufficient information. BIM allows users to build a 3D model of the historical buildings and link a variety of information to it. The post-disaster construction permits can be facilitated by BIM. Nawari et al. [46] proposed a framework that can accelerate the construction process after a disaster. BIM and Blockchain integration can be utilized in any transaction related to post-disaster construction. Consequently, extra processing fees, paperwork, and the time required to issue building permits can be eliminated. Messaoudi et al. [47] developed a BIM-based virtual permitting framework that is able to improve the efficiency of obtaining the construction permit in Post-Disaster recovery efforts. Determining the type of the construction permit, applying the newly developed permitting framework, and deciding about the result of the permit is the main procedure of the framework. Moreover, Pizzi et al. [48] utilized BIM to ease the reconstruction process after an earthquake. The main tasks of the BIM model are (1) compliance with regulatory (2) contextual modeling of various disciplines (3) clash detection among different disciplines (4) coordinating building documents. All BIM application for disaster is demonstrated in Figure 4.

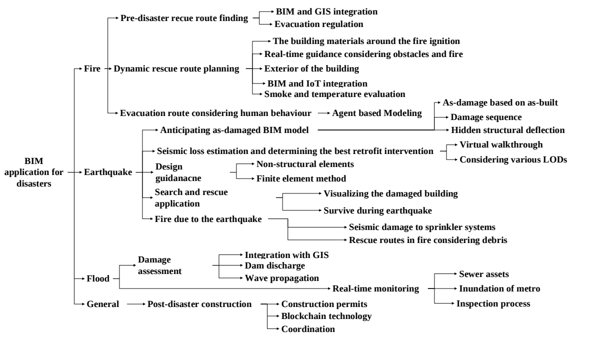

Figure 4. BIM application for disasters

5 Research gaps and future directions

Increasing the number of natural disasters makes disaster resilience an interesting research area these years. New technologies such as BIM has a great capability to enhance the resilience of the communities. After reviewing the relevant literature, existing research gaps have been detected. First, past studies have concentrated on fire, earthquakes, and floods. However, the resilience of the communities against other disaster types such as wildfires, hurricanes, and storms can be enhanced by BIM. For instance, the real-time monitoring of wildfire and bushfire stratus can be a helpful tool to reduce negative impacts. West et al. [49] argued that effective training procedures can increase the resilience of the community against wildfire and bushfire. As stated before, BIM is an ideal tool for training procedures. Second, the BIM application recovery and reconstruction process can be expanded. For example, the demolition process of damaged buildings is a critical task that can be hard without new technologies. BIM application for the demolition process is neglected in past studies. Third, most of the past studies on BIM application for disaster resilience are qualitative. More quantitative research approaches can be useful for decision-makers.

6 Conclusion

BIM applications in order to enhance disaster resilience are reviewed and classified in this paper. In order to conduct an unbiased analysis of the literature, this paper employed Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). BIM application for resilience enhancement due to fire, earthquake, and flood are studied by past researchers. Past studies generally emphasized on information transformation and visualization as two critical characteristics of BIM. Fire in buildings and finding the appropriate rescue routes, earthquake and flood damage assessment and visualizing the damages have been studied in the past. BIM can guide people to find short and safe rescue routes and prevent crowding. Earthquake damages and losses can be anticipated and visualized by BIM. Flood damage assessment can be done by integrating BIM and GIS. Findings show BIM applications have advanced in recent years but there is room for improvement when it comes to quantitative approaches. Furthermore, it is suggested that future studies could utilize the BIM application for other disasters such as bushfires. For instance, real-time monitoring, one of BIM applications, can be utilized to visualize and assess the risk of bushfire disasters. Real-time monitoring can be facilitated by using BIM and IoT integration. The findings are expected to provide useful insights to researchers in this context.

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