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Building Information Modelling supporting Safety and Security Threats Management: a Literature Review

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Abstract. The construction sector is experiencing a period of renewal in recent years, encouraged by international directives and national regulations worldwide. The most evident advances are represented by the introduction of BIM-based technology. Ensuring safety and security for the built environment is a concern for policy makers, regulations bodies, building owners and managers and for professionals. Applying BIM to address such a relevant objective can bring several benefits such as a better control over the project, greater quality and an optimized planning and execution of emergency management operations. In this paper, a systematic literature review is carried out to evaluate papers dealing with safety and security threats to civil engineering works enabled by BIM and published in 2019-2020. In particular, safety and security aspects are investigated according to three types of threats: 1. structural related issues; 2. exceptional events (e.g., atmospheric phenomena or fires); 3. external attacks or human errors (e.g. acts of terrorism or mistakes in maintenance operations). Furthermore, selected papers are classified based on the involved application domain and BIM dimension. Results show that greater attention is paid to the first and second kind of threat, while a few papers focus on the management of issues potentially caused by external attacks or human errors. The majority of the papers regards the sixth BIM dimension of different kind of buildings while infrastructures and working sites are less studied. Advantages and limitations for the BIM-based safety and security are discussed and serve as a basis for the proposal of future research directions.

Keywords: BIM, Systematic Review, Safety, Security, Threats.

1 Introduction

The construction industry sector is critically important to every national economy in terms of productivity and employment. The sector perhaps faces several problems associated with underperformance; some of these are related to poor levels of collaboration, insufficient investment in new technologies and research and development, and

inability to collect and process available data. All of this leads to mismanagement of public money (going over budget), time and manpower.

The classic methods of approaching safety and security threats to civil engineering works have highlighted enormous gaps in this sector, therefore a renewal is essential from a technological point of view and also from a methodological point of view. The Building Information Modelling (BIM) approach for safety and security threats confers greater sensitivity and efficiency in the recognition of structural errors and it optimizes costs, timing and the quality of processes.

Therefore, the concept of BIM is introduced, which properly means "modelling and management of information about a building or infrastructure". It is an approach that uses processes and technologies to support the collection and processing of data, in order to design, implement or supervise a work, a building or an infrastructure. A process based on BIM approach represents a strategic facilitator, which is applied to the orders, new constructions, maintenance, rehabilitation and redevelopment management of the built environment.

With these premises, this paper aims to provide a systematic literature review of studies for leading the application of BIM approach in safety and security threats to civil engineering works. Only recent studies conducted in the last two years are evaluated in the review for the innovations in the use of BIM as a recent phenomenon and for the technologies used that have a lot changed in the last years. A classification of the reviewed studies is proposed in order to get an overview of the current state of art and to lead future research.

The remaining part of the paper is structured into 6 sections. The next section is focused on the research method explanation. Section 3 describes the classification of the paper by BIM dimensions while Section 4 illustrates the papers by type of security threats. Discussion, conclusions and future research end the paper.

2 Research Method

The current state of the art on BIM-based methodological and technological solutions for ensuring the safety and security threats is evaluated according to the systematic literature review method. By adopting this method, authors intend to provide researchers and professionals of the field with a knowledge basis to foster the enhancement of existing processes and technology, reducing research and action time. This scientific approach aims at reducing subjectivity by providing numerous bibliographic insights [1] and by defining a research strategy characterized by a well-defined set of steps and criteria, repeatable (and therefore systematic) and updatable [2].

The research methodology is based on 4 steps:

1. Definition of the papers search criteria and execution of the research on online databases;
2. Selection of papers pertinent to the research scope based on the analysis of the abstracts;
3. Analysis of the selected full papers and further selection based on relevance to the purpose of the review;

4. Processing of the results.

In relation to the first step, the searching process was carried out on November 2020 and the following criteria were applied for searching papers on 'Web of Science' and 'Scopus' databases:

- Year of publication of the articles: 2019-2020;
- Language: English;
- Type of document: article, review, conference paper, conference review;
- Keywords combination: (BIM OR “building information modeling” OR “building information modelling” OR “building information model”) AND (Safety OR “Structural health monitoring” OR Disaster OR Emergency OR Security).

The selected keywords are generic to enable the collection of a wider set of papers to evaluate based on their abstracts and contents for our study. The researches on the two different databases show differences in relation to the nomenclature of the filters applied to exclude disciplines not involved in the topics of the review. The two search engines use a different nomenclature for the filters relating to the disciplines involved. However, an attempt was made to maintain consistency between the disciplines excluded from the results of both search engines. Specifically, the following subjects have been eliminated on Scopus: "Medicine", "Chemistry", "Agriculture", "Pharmacy", "Arts", "Healthy", "Multidisciplinary", "Economy", "Neurology" and "Immunology". On WoS, the subjects to be included in the results were selected, namely: "Engineering Civil", "Mathematics Interdisciplinary Applications", "Construction Building Technology", "Geography Physical", "Engineering Industrial", "Engineering Mechanical", "Environmental Sciences", "Engineering Electrical Electronic", "Mechanics", "Physics Applied", "Operations Research Management Science", "Telecommunications", "Public Environmental Occupational Health", "Automation Control Systems", "Social Sciences Mathematical Methods", "Engineering Environmental", "Urban Studies" and "Environmental Studies". As support was used an Excel sheet where all useful data and research steps were recorded.

In the second step, a selection process based on the abstracts analysis was carried out. Papers not related to the review topics were excluded together with 9 papers whose abstract was considered relevant but the full paper was not accessible, for example in the case of some conference proceedings. A total number of 115 papers were selected in this step.

The third step consisted in a further study of the content of selected papers, which allowed to exclude 15 papers. A final number of 77 papers was obtained by eliminating 23 duplicates from Scopus and WoS. This last database, excluding entries in common with Scopus, provided 7 papers.

The main exclusion criteria applied in the selection steps are the following:

- papers on cybersecurity;
- papers focused on workplace safety and regulations;
- papers focused exclusively on the BIM approach;

- papers on the application of BIM for purposes different from safety and security (e.g. application of BIM to support cost analysis).

The selected papers were classified in the fourth step of the research according to domains of application and BIM dimension.

The selected papers were also classified according to the physical threat for the safety and security of civil structures and infrastructures: 1. Structural damage; 2. Exceptional events (earthquakes, floods, fires, etc.); and 3. External attacks or human errors (e.g., terrorism, theft, non-compliance with safety regulations).

These results are subsequently discussed by identifying the advantages of introducing BIM for the management of built environment safety and security, the limitations and possible future directions of research in this field.

3 BIM Dimensions

BIM dimensions represent "an intuitive way to schematize the data heterogeneity in a BIM based design" [3]. There are several conventions for BIM dimensions that differ from each other beyond the fifth dimension. Specifically, some conventions identify the sixth dimension as the last one (6D). In this dimension, information on the project life cycle are processed [4]. Others attribute to the sixth dimension the task of describing the project life cycle and maintenance phase, adding a seventh dimension (7D) focused on sustainability [5]. According to some sources, a 8D BIM also exists, which involves risk analysis for the execution of the works and the subsequent monitoring in order to implement a total control over the project [6]. In this last study, Italian standards (UNI 11337 [5]) are used as the reference convention, where the 6D refers to life cycle and maintenance management, and the 7D refers to sustainability and analysis of building energy consumption.

Table 1 shows, in percentages, the number of papers grouped under each BIM dimension category:

Table 1. Papers distribution for BIM dimensions.

BIM Dimensions	% of papers
3D	19%
4D	25%
5D	6%
6D	49%
7D	1%

Results show that the majority of the analysed papers focuses on 6D BIM. This can be explained by the greater attention being paid to the importance of the building dynamic monitoring throughout its life cycle [7] [8].

Furthermore, ensuring the safety and security of a civil building necessarily involves its life cycle and maintenance management, since it is in the use phase that building

occupants' life is exposed to risk. A consistent number of 3D and 4D BIM models was also found in the selected papers sample. The spatial representation of the building, in fact, represents a characteristic that enhance the understanding of the project and, as a consequence, facilitates the identification of the threats for safety and security [9] [10] [11]. Moreover, papers where the 4D was considered, take into account production times, considering any interference in the various processing stages. Less frequent, according to the results of the research, is the involvement of the 5D. This is mainly due to the fact that 'quantity take off' or cost analyses are often related to monitoring activities and therefore they were included in the 6D (e.g., [12] [13] [14]). The 7D is the least frequent dimension investigated by selected papers as only one paper is grouped under this category [15]. Explanations for it could lie in the current distance between safety and security objectives and environmental sustainability. Interdependencies between these two domains are rarely investigated in the literature. Furthermore, the choice of the keywords set and exclusion criteria for the systematic literature review might have influenced the search results. It is worth noting that the 6D BIM addresses data which can provide the background for Safety and Security application, since it involves information for management and maintenance of the assets during the operational phase.

4 Types of Safety and Security Threat

In this section, the solutions are classified according to the type of safety and security threat to civil engineering works: 1. Structural and Installation Problems; 2. Exceptional events (earthquakes, floods, fires); and 3. External attacks or human errors (acts of terrorism, theft, non-compliance with safety regulations, etc.). This classification is defined upon the analysis of the reviewed papers, which led to the identification of these three main categories. To clarify, Human Error is clustered with External Attacks because they are considered anthropic factors. The first category addressing structural and installation problems does not include human errors such as bad construction practices or negligence, instead it refers to intrinsic issues in the building.

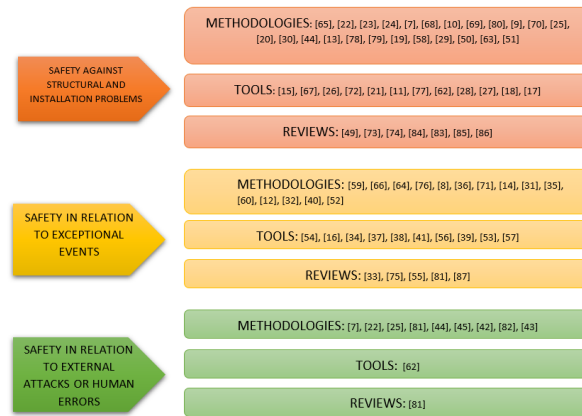
Several papers focus on multiple types of threats and because of this, they have been included in more than one category. Table 2 shows the distribution of the papers in relation to the three categories identified, while Figure 1 lists all the methodologies, tools and reviews resulting from the research performed. This overview is provided with the intent to show which is the most addressed category and which kind of papers were found in literature.

Table 2. Papers distribution by type of safety and security threats.

Type of Safety and Security Threats	% of Papers	% Type of Solutions
Structural and Installation Problems	51%	Environmental Sustainability Tools – 3%
		Data Collection Tools – 43%
		Monitoring Tools – 34%

Exceptional Events (Disasters or Emergencies)	36%	Tools for Detecting and Forecasting the Danger – 20% Environmental Sustainability Tools – 23% Data Collection Tools – 17% Monitoring Tools – 23% Tools for Detecting and Forecasting the Danger – 37%
External attacks or human errors	13%	

Fig. 1. Papers Classification by methodologies, tools and reviews



In the following sub-sections, the analysis of the solutions adopted in the papers for each category of safety and security threat is described. For each of them, a further classification is evaluated to differentiate tools and methodologies used; this distinction is made according to the types of solutions listed in Table 2.

4.1 Safety and Security Against Structural Damage and Installation Problems

Based on the type of solutions reported in Table 2, this sub-section analyses which are the purposes of using BIM-based methodologies and tools to respond to threats to structural safety.

The papers show that in the data collection phase three main objectives can be identified: 1. improve supporting technology; 2. gain more control over a large amount of data; 3. improve interoperability both between the building life cycle phases and between the project stakeholders.

Regarding the first objective, in the papers [16] and [17] Remotely Piloted Aircraft Systems (RPAS) and Unmanned Aircraft Systems (UAS), two systems for capturing images of the soil by drones, are analysed.

Regarding the second objective, the aim is to process a large amount of data through the use of new generation software: in the document [13] a large-scale 3D scan is used

and the large amount of data generated is processed with JetStream Data System; in this way, it is possible to solve geometric problems by simply comparing the model obtained by scanning with the real model with enormous precision. In the document [18], on the other hand, a software is used to allow the management of a large amount of data, so that the maintenance and monitoring costs for the safety of the structures can be easily evaluated.

Finally, the third objective, which consists in creating a common language between designers, contractors and all the other operators who actively participate in a BIM project, allows to optimize timing and significantly reduce errors [19]. The paper [20] elaborates identifiers aimed to solve the interoperability issues between spatial and temporal data from different sources.

From the papers that analyse the monitoring tools, a single common objective emerges: determining indicators that can represent a criterion for assessing the structural health of the building object during its life cycle. Several methods and software have been proposed. Among these, the Structural Health Monitoring (SHM), which allows to make continuous building objects assessments over time, taking advantage of the measurement of their vibration frequencies through sensors and supporting technologies to transform them into analysable data was one of the most cited [21] [22] [23]. Studies [10] and [24] present monitoring methodologies based on the definition of different parameters respectively for a railway network and for a road network.

The paper [25] deals with the post-disaster assessment of building objects: Virtual Permitting Framework (VPF), based on the BIM approach, includes tools capable of inspecting the building, classifying the damage, drawing up documentation for regulations compliance and using a virtual authorization procedure.

Risk detection and forecasting software applications, which also include simulation tools, are closely linked to the methods used in the monitoring and data collection phase. This implies the complementarity of the tools mentioned below with those mentioned in the papers grouped under the two previous categories.

For example, in the paper [13], Naviswork is used as a solving tool. This software digitally processes all the steel components, monitoring them throughout their life cycle to get a general picture of the health of all the elements that make up the structure.

In another case, this software application is also used together with Revit [26], where Naviswork is responsible for detecting the information related to safety problems and Revit, on the basis of this information (safety signs and the danger factors of the goods, size of machinery and signalling of other sources of danger) draws up evacuation plans to be implemented in case of emergency or other types of solutions. Revit is also used in the studies reported in papers [27], [28] and [29], demonstrating that it is a very popular BIM software for modeling different types of works, from construction sites, to buildings or infrastructures.

Finally, the research carried out produced a single result regarding the use of BIM procedures for 'sustainability' in structural safety: in the paper [34] the "environmental product declaration" (EPD) is presented. It is useful, in the design phase to select the appropriate products and materials for the construction of structures.

4.2 Safety and Security in Relation to Exceptional events

In the various stages of designing a building object, a particular attention is always reserved to safety against exceptional events. In this context, 'exceptional events' are defined as all those atmospheric and non-atmospheric phenomena, such as fires, earthquakes, hurricanes, landslides, etc., which cannot be predicted with certainty and for which emergency management strategies must be planned. From the analysis of the papers, it emerged that is important to focus on the evacuation management but at the same time the preparation phase is fundamental. A BIM approach is capable of predicting risks, monitoring the building, be prepared for this type of event by performing simulations, etc. In this way, the building occupants' health is safeguarded while limiting costs.

A consistent number of papers grouped under this type of safety threat analyses case studies focused on fires. They show fire is one of the most analysed phenomenon with the BIM approach. Papers that explore issues related to the evacuation of structures or infrastructures following an event that determines a state of emergency have also been included in this sub-section.

The papers under this category show that data collection tools and methods in safety for exceptional events category pursue the ability to improve the reading of data, the interoperability between the different project phases, the handling a large amount of data [30] [14]. In particular, the study [36] uses various software tools for the application of an innovative data collection method in the field of emergency management. Closed-Circuit Television (CCTV) makes it possible to identify congestion points along the evacuation route through a camera system, while the ResNet101 system dynamically calculates the number of people in the various areas of the structure thanks to a network of Internet of Things (IoT) sensors, identifying the riskiest areas.

In the study [31] two methods are instead integrated: the first, based on the Voxel model, dynamically synchronizes the minimum of information detected so that a change can be identified; the second based on the IFC (Industry Foundation Classes) data interchange format develops the processed information by mapping it and automatically generating solutions to possible problems. The interoperability of these two systems allows a higher level of efficiency than a model that works independently.

The objective of the studies on safety against exceptional events in the 'monitoring tools' category is to provide indicators, obtained following the analysis of the data, which can quickly and dynamically report any problem in progress [32] [33].

Among papers dealing with tools that can be used for the forecasting and detection of hazards, Ma and Wu [34] propose a methodology, called 'Fire Emergency Management System' (FEMS). This dynamically collects data through sensors and wireless networks and it is used to send alarm signals and to provide the user with information on the location of the fire and the data detected on the combustion process. FEMS allows you to determine if the fire is controllable or uncontrollable. In the second case, evacuation strategies are developed and suggested. In proposing these strategies, the emotional and panic state in the crowd during an emergency is also taken into consideration. Furthermore, the best exit route is proposed taking into account obstacles, distance, but also other parameters such as the shortest route.

The tools applicable in the category of hazard detection and prediction include simulations, which allow to obtain predictions on the dynamics of the event, to be compared with the data collected during monitoring activities and on the possible consequences. For example, in the study [35] Fire Dynamics Simulator (FDS) is used to simulate the fire in support of Agent-based Modeling (ABM) which allows to elaborate the evacuation scenario taking into account the detected factors.

In the paper [36] a methodology for the detection of the danger is formulated through the comparison between the initial position of the fire and the data obtained from the simulations performed. The tool supporting the methodology is EvacuSafe, which in documents [37] and [38] makes it possible to derive the Route Risk Index (RRI) and the risk index of the compartment (CRI), the latter based on the amount of people present in the building. Then, using Dijkstra's algorithm, a graph is extracted to find the exit path starting from any point in the building, taking into account travel time, proximity to the fire, blocking and forecasting the direction of expansion of the fire.

To dynamically update the number of people involved in an emergency, a system called Active Dynamic Signage System (ADSS) is used by the authors of [36], which communicates the direction to follow for evacuation with a dynamic signage system.

The paper [39] introduces a site evacuation methodology that includes horizontal evacuation, temporary shelter, vertical evacuation and exit evacuation.

In the study [40], it is instead proposed the calculation of the evacuation route using an algorithm A * (with variant) in the BIM environment, which involves 3 phases: in the first one, the simplified geometry of the building object and its elements is obtained; in the second one, an analysis is performed giving an order of importance to the elements present in the building objects based on safety conditions; in the third phase, the variant of the algorithm also considers the results identified in the analysis of the second phase as a parameter for the elaboration of the evacuation routes.

Finally, a methodology linked to the FDS simulation tool is presented in [52]. Combined with real-time data obtained from sensors, FDS can be used to simulate the development of fires, to predict the temperature and density of carbon monoxide, and to monitor visibility at locations throughout the entire building at any time. The Real-time Location System (RTLS) communicates with the smartphone of a building occupant, and can locate the occupant in real time with respect to the space defined in the BIM model: then the safest evacuation route is communicated. The 'risk score' (RS) is able to display the evacuation route on the occupant's smartphone with voice guidance.

4.3 Safety and Security in Relation to External Attacks or Human Errors

The type of threats that are analysed and prevented in this category relates to human action, intentional in the case of attacks and unintentional in the case of errors. In this category we will study the protocols that can help the understanding and prediction of such an event and the measures to avoid or counter it.

The paper [41] analyses the Fieldwork Protocols (FP, or the protocols followed by the police in the United States to identify dangerous situations) for stations, parks and shopping centres: although they don't definitively identify the cause of crime, they provide some evidence to clarify the links between crime and the target environment. The

result of this paper provides the basis for the Crime Prevention Through Environmental Design CPTED which, thanks to the support of the PFs, is able to make an important contribution to inspections on safety conditions in a public place.

The document [42] introduces a state-of-the-art criminological methodology that takes into account the monitoring of human behaviour, an information collection model, geometric environmental data and a modelling based on external agents to prevent man-made attacks. Monitoring can be done through various existing tools, such as closed-loop surveillance systems; the information on the construction and on the geometric data can be obtained from the bodies that deal with the monitoring of the reference system or environment. Through the Agent-Based Modelling (ABM) methodology, the probability that an event will happen in a specific place is analysed, taking into account various factors, such as the optimal environment for committing a voluntary human attack, the possible author of the act and potential victims trying to obtain as much information as this can be expected.

In this category, the possible threats caused by an involuntary human error, that is the decision variable within a semi-automated BIM methodology, should also be mentioned [7] [43] [44].

5 Discussion

The application of the BIM methodology for safety and security involves several common features that interest all the different threats categories considered in this work, namely structural safety, disaster safety and human-agent safety and security. BIM software, due to the vast data schema of IFC, can handle several data required for safety and security application, but advantages are frequently hindered by technical limitations. BIM authoring tools can provide effective modelling, increased awareness of the building characteristics and simulation power, but the exchange of the model between different software is prone to errors and inconsistencies [45]. This requires dedicated efforts to achieve seamless data exchanges and automatized procedures, which is crucial for safety and security applications. For instance, [20] adopted semantic technologies to develop a Tunnel Defect Diagnosis Systems (TDDS), based on a customized Tunnel Diagnosis Ontology (TDO) which links IFC data with other heterogeneous data coming from various systems.

In fact, BIM for safety and security threats to civil engineering works shows its full potential when supported by an overall system which handles data from several sources, from data collection to data analysis. UAS collecting data such as temperature and deformations can be linked to BIM models, in order to provide a map of monitoring points of the construction and thus predict anomalies and stresses in structural components [17]. Monitoring, prediction and prevention are key objectives of the BIM for structural safety and security threats, and they can be achieved by means of dedicated plug-ins and tailored solutions [29], [26], [46], [25]. When BIM is investigated for disaster safety, the focus mainly shifts towards simulations and risk indicators derived by monitoring tools. For instance, BIM-based simulations [47] [48] [36] allowed to discover that the shortest path is rarely the safest. These simulations took into account several

data from objects and related materials, such as inflammability, and other topological parameters such as distance from the fire source. Algorithms and real-world instances modelled in BIM environment are also important to provide meaningful and more accurate simulations [30], [58]. Finally, simulations can be even more sophisticated, considering human behavior in critical situations [14], [34], but it still a topic in full development and affected by limitations [49] [36].

Regarding BIM models, they can provide accurate 3D and sensor location data, that can be extracted in dedicated software tools which require this kind of data to simulate complex Agent Based scenarios, such as an indoor mass shooting [42], which can benefit from real time monitoring systems to save human lives. In general, safety and security applications and simulations for threats require reliable data, and BIM can provide a part of them with its 3D parametrical models, defining the simulation boundaries, while sensors and past monitoring collections are used in algorithms.

Among the limitations, the data interoperability between BIM tools act as the critical one, which affects processing times. This is a relevant issue since safety usually requires speed of execution for real time occurrences [49], [32].

As seen from literature, the BIM methodology provides an effective modelling power, which can be integrated in systems for several kind of safety and security applications, but the operative level of these solutions relies on developed algorithms, which requires higher level of maturity. Other limitations of safety and security systems can be found when implementing them. Being based on real time data collection by monitoring tools, especially in disaster safety and security application the whole system may become unavailable or ineffective, due to power interruptions caused by earthquakes or thunderstorms, or disabling factors such as smoke visual obscuration during a fire.

6 Conclusions and Future Research

Analyzing the most recent literature about BIM and safety and security threats to civil engineering works, the paper suggests to academic and industrial researchers the main fields of results currently achieved and propose a classification of them for leading also others scholars in positioning their research activities. For instance, this review highlighted the fact that the External attack and Human Errors threats are less addressed in literature if compared to the other two.

Upon the gaps and limitations found in literature, future research for BIM-based safety and security threats are several. Mainly, all the safety and security threats categories discussed in this paper share similar needs to provide better solutions. First of all, since safety and security relies on previous events to acquire knowledge and provide algorithms, enhanced and richer databases are required, possibly shared or aligned at international level [50]. This is particularly relevant for BIM-based safety simulations. Moreover, solution should consider the interoperability issue, therefore the IFC open data format should be always taken as the main element for the exchange of information between BIM tools [28], [51]. However, interoperability issues rise even for non-BIM native data, and automation to transform these raw data for BIM compatibility should

be investigated. Regarding this, semantic web technologies and dedicated algorithms can save intensive cost and time-consuming activities for data harmonization.

Besides data interoperability, increased data quality should be sought. In the implementation level, it can be achieved by better monitoring tools and equipment, such as new generation of sensors and UAS for real time data acquisition. BIM models provide detailed data about the built environment, whose information can be extracted and read for analytical or visual simulations. On this side, several experimental paths can be undertaken: for instance, VR can be explored to provide immersivity during simulations, while Bluetooth devices or smartphone app can be integrated in the safety and security system to develop a dynamic and distributed network for real time data acquisition.

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