

Review

# Building Information Modelling (BIM) to Enhance Occupational Safety in Construction Activities: Research Trends Emerging from One Decade of Studies

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**Abstract:** In recent years, the use of new technologies is rapidly transforming the way working activities are managed and carried out. In the construction industry, in particular, the use of Building Information Modelling (BIM) is ever increasing as a means to improve the performances of numerous activities. In such a context, several studies have proposed BIM as a key process to augment occupational safety effectively, considering that the construction industry still remains one of the most hazardous working sectors. The purpose of the present study is to investigate the recent research addressing the use of BIM to improve construction safety. A systematic review was performed considering journal papers that appeared in literature in the last decade. The results showed that the most viable and promising research directions concern knowledge-based solutions, design for safety improvement through BIM solutions, transversal applications of BIM, and dynamic visualization and feedback. The findings of this study also indicated that more practical BIM applications are needed, especially focusing on safety training and education, the use of BIM to augment safety climate and resilience, and the development of quantitative risk analysis to better support safety management. Overall, the study provided a comprehensive research synthesis augmenting knowledge on the role of BIM-based tools in construction safety, which can be considered a reference framework to enhance workers' safety by means of these new technologies.

**Keywords:** construction activities; building information modelling (BIM); occupational health and safety (OHS); safety management; research synthesis; systematic literature review; industry 4.0; safety resilience; safety climate

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## 1. Introduction

The fast and continuous enhancement of new technologies is rapidly changing all working sectors by providing novel tools at the disposal of companies to improve the performances of their activities. Such a revolution, sometimes called “Industry 4.0,” relies on the combined implementation of technological trends such as digitalization, cloud computing, artificial intelligence, robotization, and the Internet of Things (IoT) [1–4].

The construction industry is also influenced by these novel technological tools largely, so that some authors define such a process with the term “Construction 4.0” [5,6]. In particular, among the information and communication technologies that are transforming the construction activities, the Building Information Modelling (BIM) process [7] plays a key-role thanks to its multiple and transdisciplinary applications in the architecture, engineering, construction, and operations (AECO) industry [8]. The standard ISO 29481-1:2016 [9] defines this approach as a “shared digital representation

of physical and functional characteristics of any built object” capable of providing a reliable basis for decision-making. However, depending on the context and purpose, different definitions of BIM can be found in the literature [10]. In summary, BIM can be considered a semantically-based and object-oriented approach [11], which allows for managing a complex system of information including 3D visual aids [12–14]. The features of BIM enable the assessment of design activities and the management of all the operations within the built environment while providing a database containing both geometric and non-geometric data [15,16]. As stressed by He et al. [17], managerial applications of BIM have been attracting considerable attention from both the construction industry and academia thanks to its ability in facilitating the coordination and management of overall project information and processes related to complex project environments. In fact, the use of BIM in recent years has increased greatly, including not only the management of the design of construction features, but also the activities related to the buildings’ life-cycle such as the maintenance of the building’s assets [18–20] and their environmental performances [21]. For example, Volk et al. [22] fostered the use of BIM in existing buildings as a means to manage “as-built” documents, maintenance of warranty and service information, energy and space, emergency equipment, retrofit planning, and deconstruction processes. Other studies focused on the “green BIM”, i.e., the implementation of BIM to enhance the environmental sustainability of buildings’ life cycles [23–25].

In such a context, several studies have addressed the use of BIM for managing construction safety issues. For instance, Ganah and Godfaurd [26] investigated the relationship between BIM and the improvement of worker safety performances. With this goal in mind, starting from a literature review on communication approaches related to occupational health and safety (OHS) in construction, they carried out a survey with the goal of highlighting key factors and barriers affecting such an issue among practitioners. Similarly, Alomari et al. [27] by means of a survey of field engineers investigated the shortcomings of the use of BIM by the construction industry, focusing on the impact of the BIM’s use on a safety level. Xiaer et al. [28] investigated the use of BIM and BIM-related technologies in the design phase to improve safety management and minimize the design errors. Their review focused on BIM implementation in Design for Safety (DfS) and the related barriers. Zou et al. [29] reviewed the literature on the use of BIM in risk management. In particular, the authors provided an interesting analysis of BIM and BIM-related approaches comparing them with traditional risk management tools. However, in this study, research published up to 2015 were taken into account, and the criteria used to select them did not follow a systematic approach. Getulli et al. [30] followed a similar approach in classifying BIM-based tools focusing on Virtual Reality (VR) for improving construction safety, especially considering training activities. On one hand, all these studies underline the need of investigating the use of BIM to enhance construction OHS. On the other hand, they offer only a partial analysis on specific themes and do not take into account more recent research.

A more thorough analysis was carried out by Martínez-Aires et al. [31], who applied the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method to review research papers addressing BIM and Safety in the construction industry. In particular, the selected papers (ranging from 1981 to 2016) were assessed using as a reference framework based on the following key areas representing the BIM use as a safety management tool: Construction or Safety Management, 4D Schedule and Planning, Visualization/Simulation, Collaboration and Communication, and Identifying Hazards. For this reason, despite the noteworthy implications provided, this study offered a perspective polarized on the above factors only. Differently, Akran et al. [32] dealt with a bibliometric review of studies published in the period of 2000 to 2018, providing an inclusive science mapping of datasets aimed at correlating BIM features with safety indicators by means of visualization tools. Despite the benefits derived from bibliometric reviews [33], their limitations in providing a reliable overview of research trends should also be considered [34]. Moreover, in the recent years there was a rapid increase in the number of both studies addressing the use of BIM in general [35] as well as those focusing on construction safety research in particular [36]. Hence, it is arguable that, besides the research analyzed by the above-mentioned studies, in most recent years, a significant number of articles

have been published on the same topics. Additionally, it has to be considered that information and communications technology means change or are upgraded every three years [26] by increasing the possibility of novel solutions and approaches.

Based on the above considerations, the present study aims to update the status quo of research on the use of BIM to improve occupational safety on construction sites. This provides a systematic review of journal articles published in the last decade (2010–2019). For this purpose, a systematic literature review (SLR) following the PRISMA approach [37] was carried out by taking into account journal papers that appeared in Scopus and Web of Science in the last decade. The review of the selected studies was aimed not only at uncovering research types and specific targets, but also at depicting and discussing research streams and practical opportunities emerging in the field of construction occupational safety by means of BIM solutions. Hence, this study aims at augmenting knowledge on the role of BIM-based tools in construction safety through a comprehensive research synthesis and analysis of recent studies in literature by outlining research challenges and gaps that can be considered a reference to enhance workers' safety by means of these new technologies.

The rest of the paper is structured as follows. In the next section, the research methodology is explained by pointing out the criteria used for performing the literature review. The results achieved are illustrated in Section 3, while their discussion is provided in Section 4. Section 5 concludes the paper addressing further work.

## 2. Research Methodology

As suggested by the PRISMA guidelines [37], a systematic literature review was carried out based on the following steps.

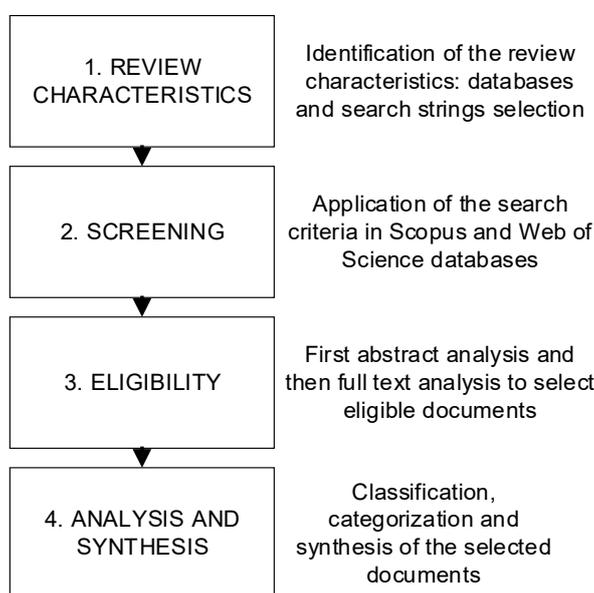
1. Identification of the review characteristics (definition of the scope, databases, and search and eligibility criteria);
2. Screening of pertinent scientific contributions (application of the search criteria);
3. Eligibility evaluation (abstract analysis for inclusion/exclusion);
4. Data analysis and synthesis (definition of the type of publication, research categories, and targets by means of the full-text review).

Such an approach, in line with other similar studies [38,39], is schematized in Figure 1, where each phase was performed in accordance with the following criteria.

- *Definition of the scope.* Scientific articles focusing on the use of BIM to improve OHS in the construction industry.
- *Databases.* Both Scopus and Web of Science databases were used since they are considered some of the most relevant sources of peer-reviewed studies [40].
- *Criteria used to carry out the screening.* Journal articles published in English between 2010 and 2019 were searched using the following search strings: "TITLE-ABS-KEY (("building information modelling" OR "building information modeling" OR "BIM") AND "safety" AND "construction\*")" for Scopus; and "(TS = (("building information modelling" OR "building information modeling" OR BIM) AND safety AND (construction\*)))" for Web of Science.
- *Eligibility evaluation.* The abstract analysis was performed to evaluate if the inclusion/exclusion of each one of the selected articles considered the scope of the review. Then, a further analysis was carried out analyzing the full text of the selected documents to verify whether they fit with the scope of the review.
- *Classification.* A first classification of the selected studies was carried out considering the main publication features of each article, i.e., publication year, affiliation country of the first author, and journal. This step can allow the definition of a first overview of research activities on the use of BIM for safety purposes in the last decade.
- *Categorization.* The selected studies were analyzed based on the type of each article, i.e., empirical or conceptual studies, which is in line with similar examples proposed in literature [39,41,42].

More in detail, such a distinction into empirical and conceptual research was made based on the following criteria: “conceptual study” is referred to those studies that provide theoretical concepts, theoretical models, and frameworks as well as literature reviews. At the same time, “empirical study” pertains to those studies addressing novel technical solutions, surveys among stakeholders, or practical case studies of BIM implementation to improve occupational safety.

- *Research targets.* The selected studies were further analyzed with the goal of bringing to light their specific target as well as the means to achieve it. In such a context, the analyses provided by both Zou et al. [29] and Getuli et al. [30] were used as a starting point. Hence, based on these cues, a novel set of research targets emerging from the literature was defined: knowledge-based systems, automatic rule-checking systems, scheduling information, overlaps and clashes resolution, proactive feedback, training, stakeholders’ perception, and workers’ behavior studies. In Table 1, a description of these targets is provided.



**Figure 1.** Scheme of the proposed systematic literature review approach.

**Table 1.** Classification of the target types of the selected studies.

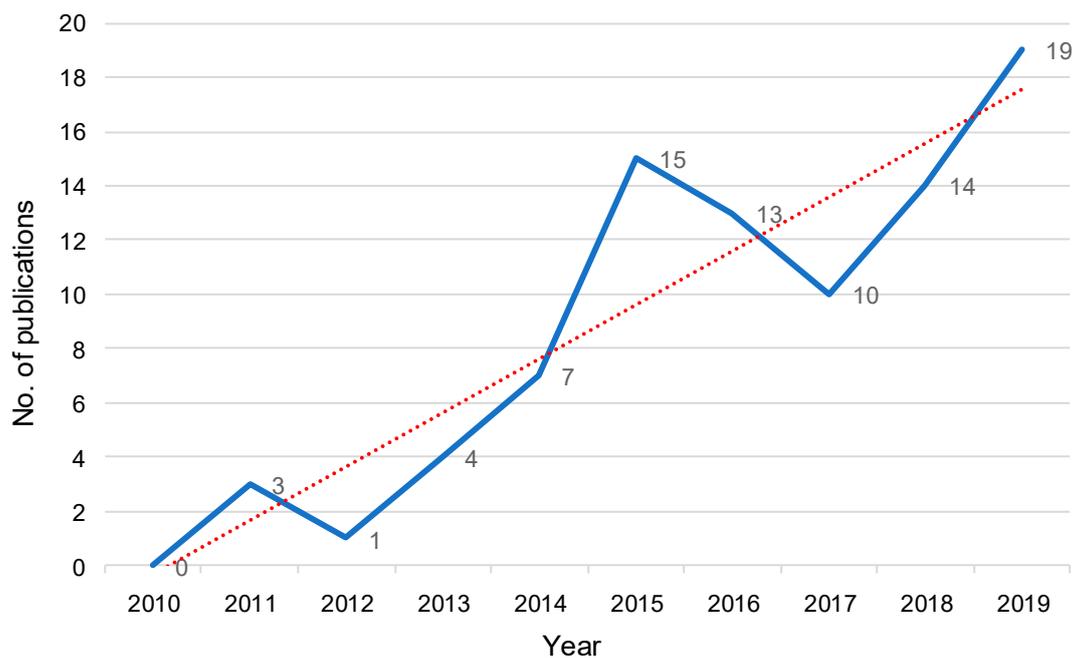
Code	Target	Description
T.1	Knowledge-based systems	BIM provides information to knowledge management systems, supporting decision making for risk assessment and management, especially by identifying safety risks during the planning and design phases.
T.2	Automatic rule checking	Codified safety rules are implemented in a BIM-based platform, which allows designers to verify the conformity of both object configurations (e.g., spaces, distances, and dimensions) and processes (e.g., construction sequences and tasks).
T.3	Scheduling information	Studies focusing on the use of BIM-based models to augment dynamic visualization of safety procedures.
T.4	Overlapping and clash detection	BIM models can allow designers to detect space conflicts (e.g., workspaces, equipment), task overlaps, and site congestions.
T.5	Proactive feedback	The combination of BIM with proactive technologies can allow real-time warnings and feedback: tracking the dynamic position of materials, workers, and equipment, and monitoring the presence of hazards and obstacles.
T.6	Training	Studies addressing the use of BIM models and the related technologies that can be used for education and training purposes (e.g., training of workers, students, and safety managers).
T.7	Stakeholders’ perception	Surveys on the use of BIM to improve safety in construction activities by highlighting the benefits of and barriers to its use.
T.8	Workers’ behavior	BIM based/compliant tracking systems to recognize the behavior of workers.

### 3. Results

Following the above criteria, in the first stage of the analysis, 343 documents emerged from the search into the databases (157 from Scopus and 186 from Web of Science), which resulted in 223 different articles excluding duplicates. Then, the eligibility evaluation, performed in two steps (abstract analysis and full-text analysis) led us to select 86 documents, which are listed in Appendix A (Table A1). Such a number as well as the documents' classification, categorization, and target definition are the outcome of a multiple session assessment. These analyses were carried out by both authors independently. Then, results were discussed in several meetings until the convergence of the output was achieved. This process can allow the reduction of the assessors' bias, making the final selection more reliable, as suggested by Vinayak and Kodali [43]. The eligibility assessment was focused on selecting those papers addressing the use of BIM and related tools for improving occupational safety in construction activities explicitly in a theoretical or practical manner. Hence, studies dealing with structural safety, equipment selection, facility management, logistics, etc. were excluded, even though these issues were partially linked to safety.

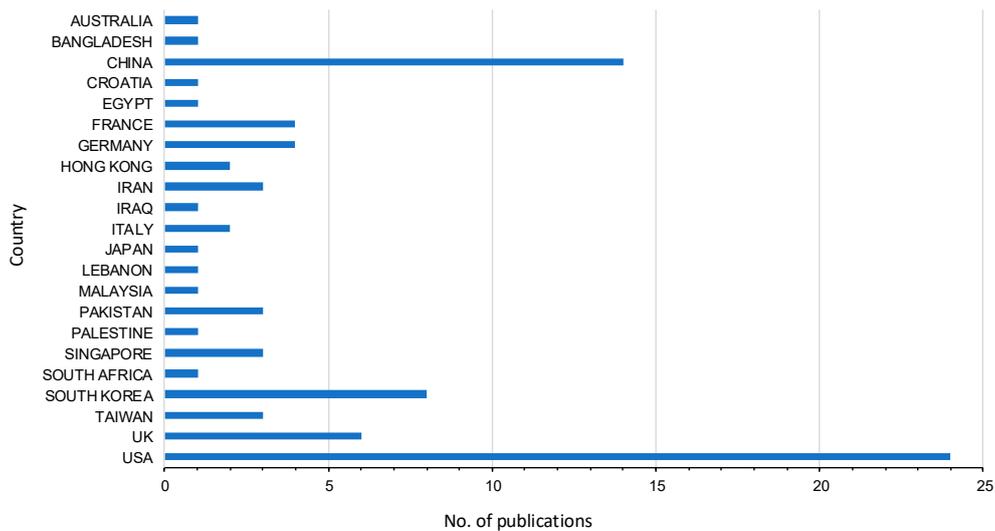
#### 3.1. Classification and Categorization

The first step of the analysis provided a screenshot of the different typologies of the selected documents by considering the publication year, the type of journal, and the country of the first author. In Figure 2, the evolution of the publications addressing the use of BIM for OHS purposes is represented.



**Figure 2.** Temporal allocation of the selected publications (the dotted red line represents the linear tendency, while the solid blue line follows the number of publications per year).

The distribution of the articles in the selected period (2010–2019) shows that, while in the first years of the last decade a few studies faced the use of BIM to improve workers' safety in construction activities, the interest of researchers in such a process has increased largely in recent times. These studies were published in 38 different journals (see Appendix A) by first authors belonging to 22 different countries where USA, China, and South Korea represent the majority of contributors (Figure 3).

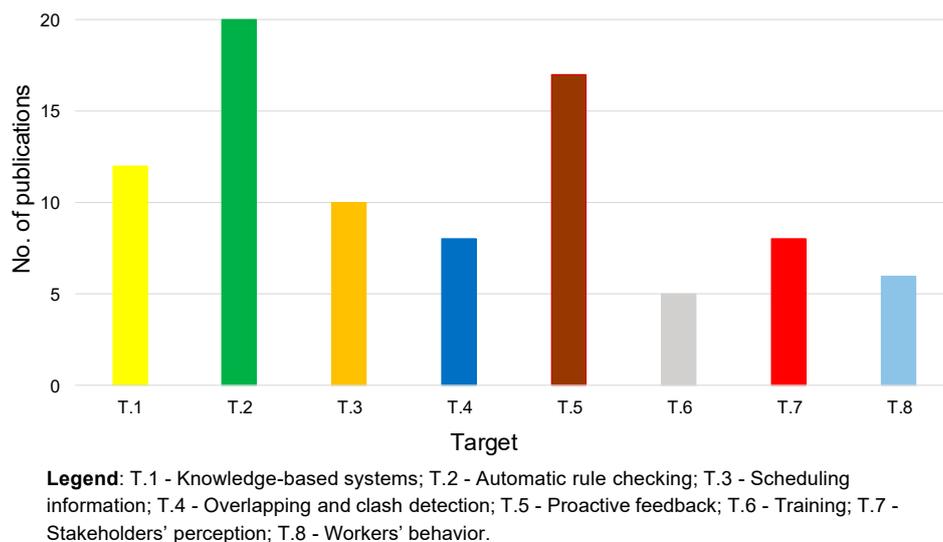


**Figure 3.** Number of publications per country (the country of the first author is considered).

Lastly, the research type was analyzed to better categorize the selected studies. As a result, it emerged that the number of conceptual studies (51) is higher than that related to empirical studies (35) by outlining a prevalence of theoretical research.

### 3.2. Research Targets

A further analysis of the selected contributions consisted in eliciting the objectives of each study, which were grouped in accordance with the research target categories illustrated in the previous section. As shown in Figure 4, the largest group of studies is related to research focusing on the development of automatic rule checking solutions (T.2), and studies dealing with proactive models (T.5), which flowed by those addressing BIM-based knowledge management systems (T.1). Conversely, it emerged that few articles studied BIM-based tools for training activities (T.6) as well as a small number that dealt with workers' behavior (T.8).



**Figure 4.** Number of publications per research target.

In the following subsections, a more detailed description of these studies is provided since they represent the emerging research issues on implementing BIM-based tools to improve occupational safety in construction activities.

### 3.2.1. Knowledge-Based Systems

Most studies classified within this research trend are based on the development of a knowledge-based system for safety management integrating a BIM platform, where the database for safety management is based on the analysis of safety regulations, documents, and best practices [44]. Accordingly, the majority of these studies rely on the Prevention through Design (PtD) approach by proposing a framework for risk assessment to be used at a project level. Jin et al. [45], for example, developed a methodology focusing on the top levels of the hierarchy of controls, which enables possibilities for eliminating or mitigating risks before they are present on sites. In order to standardize the description of each aspect of risk knowledge, facilitating the knowledge reasoning and retrieval, Ding et al. integrated ontology and semantic web tools [46]. Hossain et al. [47] proposed a Design for Safety (DfS) library aiming at integrating BIM with a risk review system providing a constraint model to store the formalized safety suggestions. Similarly, Mihić et al. [48] developed the requirements for defining a database of construction hazards to be implemented in a BIM environment by focusing on hazards and activities needed for constructing structural elements of a building. The development of specific modules for risk assessment databases was also considered by Deng et al. [49] who implemented safety management modules based on the secondary development of Revit platforms for identifying relevant hazard sources. Other studies dealt with specific construction types such as proposing a tailored Risk Breakdown Structure (RBS) for a BIM-based risk management framework for bridge projects [50]. Zhang et al. [51] developed a BIM-based Risk Identification Expert System (B-RIES) for tunnel construction. Differently, two studies proposed research frameworks where data retrieval for the database implementation are based on information about past accident cases [52] and near misses reporting information [53]. We included the research of Zou et al. in this category [29] who provided a thorough survey of studies addressing BIM and related technologies. This research provided a clearer distinction between the different typologies of contributions and synthesizing of their analysis in a general risk management framework, where knowledge management plays a central role. Similarly, the study by Hallowell et al. [54] proposed a review of information technology for construction safety by developing a framework that integrates empirical safety risk data with building information modelling and other technologies for an attribute-based risk assessment.

### 3.2.2. Automatic Rule Checking

A large number of studies dealt with the development of rule checking tools. In particular, two studies focused on implementing the Intelligent Productivity and Safety System (IPASS) framework [55,56], which is capable of highlighting high-risk areas during the design stage and enabling hazard mitigation strategies to be applied at the project level. Other studies proposed a more managerial approach for construction safety based on rule checking of site planning [57–59]. In order to augment the effectiveness of the information that supports the identification of the rules, Zhang et al. [60] proposed an ontology-based job hazard analysis (JHA) approach for safety planning, while Malekitabar et al. [61] based their implementation on the analysis of accidents by depicting a set of accidental drivers linked with safety rules. Other studies presented BIM-based rule checking approaches in specific contexts. For example, Li et al. [62] developed a BIM-based risk recognition methodology for the recognition of safety risks for underground construction at the pre-construction stage while Luo and Gong [63] implemented BIM-based code compliance checking for deep foundation works. In such a context, the contribution of Kan et al. [64] is in addressing excavation planning by implementing a tool for automated safety excavation modeling approach compliance with safety regulations and best practices by relying on visual programming and BIM technologies for safety management. Prevention through Design (PtD) is at the base of the model proposed by Qi et al. [65] in the development of a framework for a “static” checking for compliance with specific safety requirements, which is proposed for two different software environments. Such an approach is aimed at automatically checking for fall hazards in building information models by providing design alternatives to users. Fall hazards are also the focus of the model proposed by Melzner et al. [66]

who presented a tool for detecting potential fall hazards using the industry foundation classes (IFC) design model and providing safety protective equipment measures based on predefined rule sets. Similarly, Zhang et al. [15] developed a table-based safety rule translation algorithm based on the Occupational Safety and Health Administration (OSHA) rules for fall protection and other construction best practices in safety and health, which, in its further evolution [67], allows the identification of potential fall hazards dynamically based on the construction schedule. Other studies proposed the implementation of automatic rule checking for planning the safe use of work equipment such as tower cranes [68] and scaffolding [69–71]. In addition, a semi-automated rule checking tool for identifying fall and cave-in hazards related to excavation pits and models was proposed by Wang et al. [72]. Lastly, Sadeghi et al. [73] proposed an analysis of studies dealing with BIM-based technologies for construction safety by focusing on their use for improving scaffolding systems and potential fall hazards by means of automated rule checking approaches.

### 3.2.3. Scheduling Information

To improve the dynamic visualization of safety procedures and safe paths for workers on the construction sites, 4-dimensional BIM models were presented for identifying hazardous areas and the suggestion of optimal paths [74] as well as for defining safe evacuation routes [75] in an automated manner. Similarly, other studies [76–78] focused on the automatic generation of temporary structures such as scaffolds by proposing 4-dimensional support for generating multiple plans based on spatiotemporal information of the activities associated with BIM. This allows designers to select the optimal and safer solution. Other research addressed the implementation of scheduling information tools to support designers in solving schedules' conflicts in railroad [79] and bridge construction activities [80]. A more specific study by Xie et al. [81] tackled the implementation of a BIM-based framework augmented by virtual reality tools for the safe execution of job sequences related to the steel structure erection. In addition, it is worth mentioning the multi-criteria decision making (MCDM) approach used by Marzouk and Al Daour [82] for scheduling optimization of the excavation works on a construction site, while Abed et al. [83] developed a 4-dimensional BIM-based platform to generate a specific time schedule to prevent fall hazards.

### 3.2.4. Overlapping and Clash Detection

In this group of papers, studies addressing safety clashes are considered where “construction safety clashes” can be defined using the words of Tixier et al. (p. 3) [84] as those “incompatibilities among fundamental attributes of the work environment that contribute to construction injuries.” Accordingly, the above-mentioned study proposed an approach based on data mining to identify potential safety clashes from a data set of attributes extracted from injury reports merging BIM and advanced work packaging (AWP) tools. Two studies by Zhang and Hu [85,86] proposed a 4-dimensional BIM space–time model for site entities that integrate traditional site layout management and dynamic collision detection. Trajectories of workers operating in the construction site were analyzed by Arslan et al. [87] with the aim of detecting the proximity of workers and machinery to avoid collisions as well as controlling unauthorized access of users to hazardous site areas. Zhang et al. [88] focused on detecting workspace conflicts by means of the geometric conditions of different settings in the workspace with the goal of identifying workspace congestion and safety hazards. Unsafe situations such as collisions of structure, equipment, and machinery due to the improper design of time arrangement and space layout at the construction site were tackled by Yi et al. [89] who discussed the safety management of tower cranes in particular. Similarly, tower crane operations were investigated by Lee et al. [90] who developed a tower crane navigation system based on BIM to avoid collisions when operating the crane with blind spots. Al Hattab et al. [91] developed a simulation model to provide possible scenarios of overlapping when using tower cranes in order to make tasks falling in the overlap zone safer.

### 3.2.5. Proactive Feedback

Numerous studies faced the development of BIM-based proactive models for safety improvement. For instance, Choe and Leite [92] proposed a proactive site safety planning framework relying on both temporal and spatial inputs, which allows an assessment of work period and work zone safety by means of the integrating activity safety data with a project schedule and a 3D visualization model. Riaz et al. [93] proposed a model named Confined Space Monitoring System (CoSMoS), which integrates real-time monitoring of sensor data with BIM providing a proactive monitoring system to improve workers' safety. Such a tool was further improved in order to deal with safety issues of confined spaces [94]. Similarly, Arslan et al. [95] proposed a model for real-time environmental monitoring, visualization, and notification system integrating BIM with radio frequency identification (RFID) and wireless sensor networks (WSNs) tools. Costin et al. [96] used RFID integration with BIM to develop a system for real-time tracking of workers on the construction site. Accordingly, Arslan et al. [97] proposed a tool, named WoTAS (Worker Trajectory Analysis System), for the visualization of workers' movements in order to monitor critical building locations and identify potentially unsafe incidents on the construction sites. Other BIM-based solutions for proactive monitoring of construction sites were discussed by Tagliabue et al. [98], who analyzed four different practical cases. Li et al. [99] combined a knowledge management tool (called a Safety Risk Identification System (SRIS)) with a warning system (Safety Risk Early Warning System (SREWS)), where the latter allows the integration of safety information in the BIM platform and provides the dynamic positioning and tracking of unsafe processes in a three-dimensional space. With a similar purpose, Park et al. [100] merged BIM, cloud-based communication technology and Bluetooth low-energy (BLE) based sensors by developing an automated monitoring system for the real-time proactive detection and reporting of unsafe incidents through a tracking sensor system. More specific solutions were proposed to address particular safety issues. For example, Wu et al. [101] developed a BIM-based monitoring system to support engineers in identifying and assessing risks during urban deep excavation projects. Golovina et al. [102] developed a risk assessment framework based on spatiotemporal global positioning systems (GPS), which provides real-time hazard index heat maps that can proactively visualize struck-by and near-miss interactions between workers-on-foot and equipment. In a further study [103], an algorithm for the quantitative analysis of near-hits events was developed, which introduced a graphical user interface that can provide safety managers with automatically generated safety information on near hits. The risks of striking rebar and buried utility lines during drilling operations to place embeds into reinforced concrete decks were tackled by Akula et al. [104] who proposed a feedback algorithm that warns the drilling operators. Other studies dealt with gas detection systems based on the integration of BIM with wireless sensor network (WSN) technologies to improve the safety management of hazardous gases in underground construction sites [105], while Smaoui et al. [106] proposed a prototype system merging real-time monitoring of toxic dust, worker location tracking, and BIM visualization technologies. Lastly, the research of Park et al. [107] studied the implementation of a hybrid-tracking system that integrates Bluetooth low energy (BLE) technology, motion sensors, and BIM in order to reduce tracking errors. In this group of studies, a review was proposed by Forsythe [108], who analyzed recent works by addressing proactive solutions based on building information modelling (BIM) and focusing on the real-time locating technology, which can be used to determine where workers and objects are on site at any point in time, and highlighting the difference between them and those dealing with 4-dimensional process simulations since they were considered more suited to pre-construction planning situations.

### 3.2.6. Training

Safety management and visualization system (SMVS), which integrates BIM, augmented reality (AR), location tracking, and game engine technologies, was proposed by Park and Kim [109] for both inspection, and safety education and training purposes. Such a tool relies on accident cases, training material, and inspection checklists' databases. Clevenger et al. [110] developed a prototype of an interactive, BIM-enabled, safety training module on scaffolding, which was tested among university

students. Similarly, Liu et al. [111] implemented a visualization tool of scaffolding that simulates safety passages and temporary stairs by proposing preventative measures to reduce errors that can occur when installing scaffolds. Instead, Li et al. [112] implemented a BIM-related proactive behavior-based safety (PBBS) approach aimed at providing real-time warnings and post real-time analyses for safety training by means of automatically monitoring and recording workers' unsafe location-based behaviors. In addition, Getuli et al. [30] focused on the analysis of BIM and other technologies, such as virtual reality (VR). The researchers proposed a general framework to classify them and provided practical examples on their application for safety training.

### 3.2.7. Stakeholders' Perception

Most studies in this category discussed the results of surveys carried out at a national level among health and safety professionals, engineers, architects, and contractors operating in the construction sector on BIM-based tools for enhancing safety. For example, Marefat et al. [113] surveyed professionals with the aim of identifying BIM functions and BIM benefits for construction safety, as well as determining the potential barriers to BIM implementation in the Iranian construction industry. Swallow and Zulu [114] investigated the current perception of professionals of the benefits and barriers to the adoption of 4-dimensional modeling for managing construction site safety in the UK, while Enhassi et al. [115] conducted a similar study in the Gaza Strip-Palestine. Similarly, Zulkifili et al. [116] analyzed the potential of the automated safety rule checking (ASRC) system in Malaysia BIM-based projects as well as its improvement options. Alomari et al. [27] discussed the results of an on-line survey by providing an econometric analysis to better understand variables statistically linked to the impact of BIM on the enhancement of construction safety, such as age, experience, job title, and project delivery methods. Other studies carried out an investigation on the students' awareness and perception of the value of BIM and 4D technologies for creating safety enhancement by highlighting the importance of the inclusion of BIM in the education of professionals [117]. Differently, Ganah and John [26,118] conducted two studies aimed at investigating the position of the practitioners' perception with respect to site operatives on BIM usage for health and safety management on-site, especially by focusing on the communication aspects such as toolbox meetings, whose effectiveness can be augmented by means of visualization tools.

### 3.2.8. Workers' Behaviour

Among the studies that addressed the behavior of construction workers, the majority focused on the development of proactive systems that are able to track workers to better understand their behavior. For instance, Dong et al. [119] developed a system for automatically identifying personal protective equipment (PPE) misuse by means of the integration of BIM-based positioning technology and pressure sensors. This combination allows the assessment of the personal safety performance of workers based on their responses to danger warnings. Li et al. [120] integrated the behavior-based safety (BBS) approach with the technology of the proactive construction management system (PCMS) in order to identify critical safety behaviors and goals, which allowed safety managers to improve safety awareness and correct unsafe behaviors. Similarly, Lee et al. [121] proposed a framework for the dynamic analysis of BBS risks that can support safety managers in inspecting and managing the workers' behavior by observing and recording the unsafe behavior based on a BBS checklist. In addition, Arslan et al. [122] developed a prototype named visualizing intrusions in dynamic environments for worker safety (VIDEWS). This system augments the BBS approach by integrating BIM with Bluetooth low energy (BLE) beacons and wi-fi enabled handheld devices in order to track movements on the construction site for a movement-related behaviors analysis. The analysis of intrusions, i.e., unauthorized entries in hazardous areas on a construction site, is also the object of the research by Shuang et al. [123], who collected movement data in a real construction site by providing an analysis of this kind of rule-breaking behavior on a large scale while considering parameters such as the workers' age and gender. Lastly, Olugboyege and Windapo [124] proposed a review of research studies focusing on the

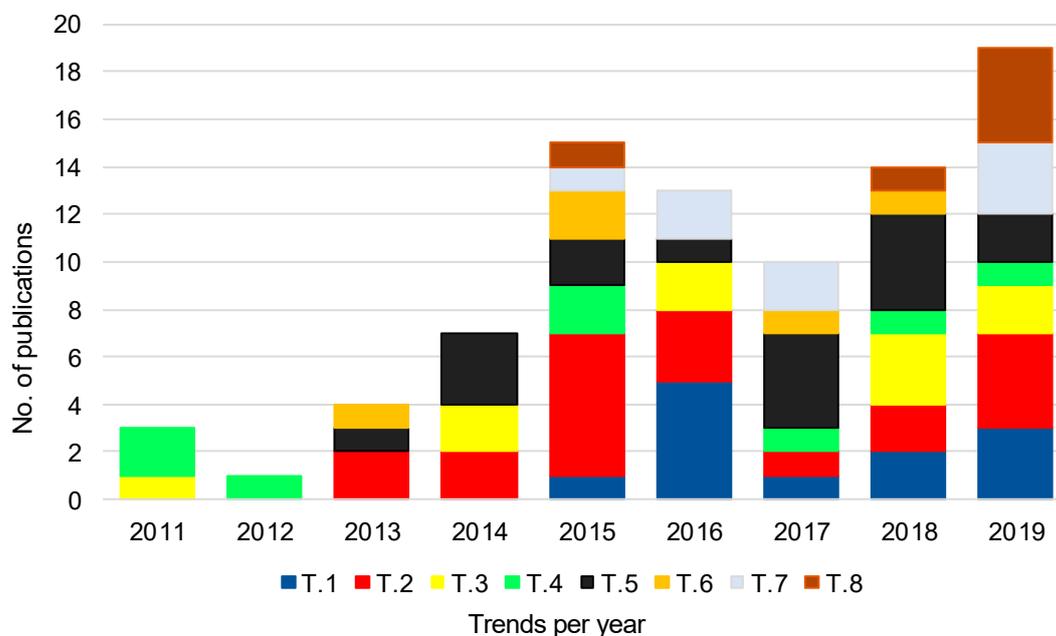
use of BIM-based tools to augment construction safety culture and providing a conceptual framework based on a theoretical grounding approach, which depicts a transition from the safety management system to safety behavior, and then from safety behavior to a safety climate.

## 4. Discussion

### 4.1. Discussion of Results

The analysis of the results allowed us to elicit a thorough framework of research activities on BIM application for occupational safety in the construction industry.

First, from a temporal perspective, the results showed increasing interest in this research field in recent years. Actually, the majority of studies were published in the second half of the considered decade (2015–2019), while, in the period 2010–2014, only 15 articles were reported. Although one might consider such an output very obvious since this trend can be correlated to the ever-growing availability and power of information technologies, it is noteworthy that some research trends, such as T.1 (knowledge-based systems), T.6 (training tools), T.7 (stakeholders' perception), and T.8 (workers' behavior), have been researched only recently (Figure 5).



**Legend:** T.1 - Knowledge-based systems; T.2 - Automatic rule checking; T.3 - Scheduling information; T.4 - Overlapping and clash detection; T.5 - Proactive feedback; T.6 - Training; T.7 - Stakeholders' perception; T.8 - Workers' behavior.

**Figure 5.** Research targets of publications per year from 2011–2019.

These emerging research trends represent an important aspect of the study by pointing out current challenges in the development of BIM-based OHS solutions, which can be summarized as follows.

#### 4.1.1. Knowledge-Based Solutions

The interest in developing knowledge-based systems augmented by BIM technologies appears constant in recent years. This aspect further underlines the need for improving safety knowledge management and risk knowledge management in construction activities, especially in complex systems, which is in line with other studies [125–128]. The analysis of the literature shows that the use of BIM-based tools can augment the performances of knowledge-based solutions [51] by providing not only the automated identification of safety risks and the corresponding safety design preventive measures, but also reducing the flaws due to the information exchange between building models

and safety assessment tools, which facilitates risk communication and support dynamically [29,47]. Moreover, the function of “one modification, everywhere modification” can reduce the designers’ workload and time of information processing [50]. A promising approach for improving this type of tools is represented by integrating a database with information related to accident cases [52], which can reduce the possibility of underestimating the combination of different causalities [129]. Similarly, the inclusion of the near-miss reporting information could be greatly enhanced by visualizing not only risk assessment purposes [53], but also for the implementation of proactive models [102]. For training purposes, it can augment the risk recognition capacity of workers, which makes the real-time communication between safety managers and workers more effective [109].

#### 4.1.2. Awareness on BIM Applications for Construction Safety

Another aspect that emerged in the recent literature is related to the analysis of the stakeholders’ perception toward BIM solutions for construction safety. In fact, several studies aimed at bringing to light benefits and limitations in applying BIM to enhance the health and safety of workers from 2015 to 2019. In such a context, it emerged that experienced safety managers are reluctant to use BIM technologies since they think that they can hardly augment the project safety level over the traditional approaches [27]. Moreover, the quick and continuous update process of software tools is also a barrier in terms of both investment costs and human resources training [26]. To improve such hindrances, the inclusion of specific BIM modules in the curricula of future architects, engineers, and safety professionals is deemed very beneficial since it can foster safety training and education more effectively.

#### 4.1.3. Design for Safety Improvement through BIM Solutions

As per Jin et al. [45], proactive identification and elimination of potential construction hazards is safer and more cost effective than their traditional (reactive) management. In such a context, another remarkable issue that emerged from the analysis is related to the attention paid to the “Design for Safety” or “Prevention through Design” approach [46,55,65], which is considered the most promising concept to achieve the “zero accident” vision in the construction industry [44] and the most effective intervention of risk reduction, according to the hierarchy of controls [130]. BIM-based tools can allow designers to implement new approaches for minimizing hazards and risks since the first stages of such a hierarchy involve all construction stakeholders and foster the communication and data exchange among them.

#### 4.1.4. Transversal Applications of BIM

The role that BIM-based tools can play in safety training is another noteworthy issue coming out from the analysis since they can generate a persistent effect of construction safety [112], which provides immersive environments thanks to which workers can experience safe insights on the way the various construction activities should be carried out properly [30], including emergency and evacuation operations [49,75,82,95]. The latter aspect also demonstrates that BIM applications can be considered “transversal” toward the research trends used to classify the selected documents since they can be used for different safety issues at the same time. Similarly, from the analysis, it emerged that other aspects were addressed in different research contexts, such as scaffolding planning and installation (e.g., in [64,70,71,78,111,112]) and fall hazards (e.g., in [15,58,64–67,72,83]). These multifaceted applications of BIM technologies can be observed for a better management of workers and equipment mobility on the construction site to avoid clashes and crashes (e.g., in [49,79,84,86,88,98,102,122]). Accordingly, on one hand, these studies revealed the benefits that can be achieved by implementing BIM models for the assessment and management of some typical construction risks, which are traditionally of major concern in the sector [131–134]. On the other hand, this issue can represent a base for further research addressing the implementation of BIM-based solutions to achieve transversal safety goals.

#### 4.1.5. Dynamic Visualization and Feedback

Another very promising research stream is related to implementing BIM-related tools to allow dynamic visualization of working procedures, which provides immediate warnings in case of the unsafe behavior of workers. Such use of BIM-based tools can enhance the safety of construction sites effectively since they can act at a more practical level, e.g., monitoring the use of PPE, allowing a real-time and dynamic tracking of the position of both worker and equipment, and revolving worksite conflicts dynamically [30,80,103,119]. In such a context, the implementation of BIM solutions for monitoring the behavior of workers represents a current research challenge, not only at the individual level, but also by focusing on the interactions with other workers and the construction site.

#### 4.2. Research Insights

Summarizing the output of the analysis of the selected documents, several practical implications can be outlined as prominent issues, which can contribute to reduce current research gaps augmenting knowledge on the use of BIM-based tools for construction OHS.

- These tools are very important for understanding the dynamics of construction activities and the related hazard types. Hence, they can support safety training and education of workers effectively. In line with Choe and Leite [135], this can also allow safety managers to prepare safety actions more adequately. However, from the analysis, it emerged that the use of BIM for safety training and education has not been investigated sufficiently. Thus, future research directions should focus on these applications of BIM-based tools.
- As highlighted by several studies [26,27,124], the implementation of BIM technologies can enhance safety culture and, hence, safety climate, among all the operators (field workers, managers, and engineers) since they can augment their ability to monitor the safe execution of construction activities as well as respond to external changes and anticipate future incidents. Overall, these applications show a transition of construction safety management from reactive into proactive approaches. Consistent with Chen et al. [136], both the above aspects, awareness and anticipation, represent key factors of resilience in the construction safety context. Accordingly, proactive BIM models can fit with the proactive approach of resilience, which is the core of effective safety management [137]. This aspect is also consistent with the findings of Yap and Lee [138], who underlined the importance of the commitment of the construction personnel and operatives in enhancing safety. Nevertheless, such issues still deserve research efforts.
- The majority of documents proposed conceptual research. Moreover, considering that, in the empirical studies, research relying on surveys is included, few practical applications of BIM-based solutions were observed. This aspect sheds light on the insufficient technology transition from construction safety research into practice. Such a finding confirms research clues suggested by several recent studies [126,139], which asked for more practical applications of Industry 4.0 technologies to enhance construction safety.
- The analysis also highlighted that another knowledge gap is represented by the scarcity of studies aimed at implementing BIM-based tools for quantitative risk analysis to better support safety management [29,103,120]. To reduce such a limitation, it is deemed that further research is needed for developing BIM solutions for a more objective risk assessment.
- This review indicated that, when analyzing the barriers for implementing BIM solutions for OHS, most studies focused on two major gaps: the need for a higher level of standardization for maximizing the capability of these tools [46,63] and the necessity of a proper training of all the stakeholders interacting with them [55,97,114]. Accordingly, to augment the usability and spreading of OHS BIM solutions, these two research issues are worth further investigation. In fact, while the former can contribute to making BIM-related tools available for small projects, which is in line with the research cues stressed by Olbina et al. [140], the latter is consistent with the

suggestions of Cortés-Pérez et al. [128]. Both of them represent key factors in improving safety communications among the construction operators.

- Another remarkable aspect that emerged from the analysis is represented by the possibility of integrating BIM with different types of tools for multipurpose applications. In fact, studies aimed at merging BIM with other technologies such as sensors, GPS, virtual reality tools, etc. are increasing in recent years, especially to develop proactive solutions. Since this ability to combine different technologies can turn “Industry 4.0” into a reality in OHS [141], BIM-based technologies can play a fundamental role for developing “Safety 4.0” in the construction industry. Consequently, this aspect represents a promising research trend to further develop and achieve an integrated construction safety 4.0 environment.
- Furthermore, it is worth pointing out the effort paid to develop BIM-based models for the safety improvement at the design and planning stages of construction operations [15,36,44,65]. In such a context, the development of integrated working procedures, combining technical and safety issues, for a proper movement and positioning of the workforce by means of wearable devices integrated into PPE represent a valuable research stream, which can be extended in other industrial sectors as well as toward different hazard types than the traditional ones.

Lastly, the research targets listed in Table 1 represent the first attempt to classify research categories in the field of BIM-based applications for construction safety. On one hand, such a list, which was based on the analysis of the selected documents, can be considered as a reference framework for further research. On the other hand, it is certainly not exhaustive and novel categories that can be included by future studies.

#### 4.3. Study Limitations

Besides the above positive aspects, the limitations of this study also have to be addressed, starting from those that are usually related to literature reviews, i.e., the criteria used to select the documents. In fact, limiting the choice to studies focusing on OHS of construction works led us to exclude numerous relevant contributions on the use of BIM in construction-related areas such as facility management, fire safety, structural safety diagnosis, or work equipment selection. Similarly, the use of two databases only (Scopus and Web of Science) can reduce the general validity of the study. Hence, the output of this study cannot be considered exhaustive and it should be evaluated in its specific context [142,143].

In addition, it has to be mentioned that the literature review carried out in this study did not take into account the impact of the journals where they were published, e.g., filtering them based on the Cite Score provided by Scopus or the Journal Impact Factor by Web of Science. Acknowledging that this can represent a limit of the study, the reasons of such a choice can be summarized as follows. (1) the literature search relied on the quality criteria of acceptance provided by the above-mentioned databases and a further filtering would have reduced the sample size, especially disadvantaging recent journals, and (2) the differences between the parameters are used to calculate the impact of articles by Scopus and Web of Science.

Lastly, it is worth noting that one might reasonably argue a more thorough classification of the research trends listed in Table 1 could have included the definition of sub-categories. However, due to the multifaceted applications of the BIM-based tools and approaches that emerged in literature, this point was not considered by the authors, believing that a more detailed classification could lead to the definition of heterogeneous subcategories.

## 5. Conclusions

Occupational safety in the construction industry is of major concern worldwide since the number of accidents is always considerable. In recent years, the development of technology has provided new tools such as BIM-based models, which turned out to be an effective means to deal with OHS problems. The present study aimed at investigating the research status quo on the use of BIM to improve OHS

in the construction industry. With this goal in mind, a sample of 85 documents was identified and reviewed by focusing on the analysis of research streams on the use of BIM technologies for OHS purposes. Accordingly, a general framework to categorize the selected research was defined in order to point out the emerging research issues and advancements on this topic. The analysis brought to light the versatility of BIM-based processes and tools in supporting different OHS issues, varying from the design and planning stages of the construction site to monitoring of the workers' unsafe behavior on site.

On the whole, the contribution of the study does not rely only on providing a general overview on the status quo of BIM applications to enhance occupational safety in construction works, but also in the elicitation of research trends and emerging themes in the last decade of literature. With this goal in mind, eight research trends were identified to classify BIM technologies for construction safety: knowledge-based systems, automatic rule-checking systems, scheduling information, overlaps and clashes resolution, proactive feedback, training, stakeholders' perception, and workers' behavior.

Based on this, several research challenges were elicited and discussed as viable implementations and promising approaches on the use of BIM-related tools for construction safety, such as: knowledge-based solutions, design for safety improvement through BIM solutions, transversal applications of BIM, dynamic visualization, and feedback. Additionally, practical implications and research gaps were outlined to address further research. In such a context, the findings of the study indicate that more practical applications are needed, especially those focusing on the use of BIM for safety training and education, its role in augmenting safety climate and resilience, and the development of quantitative risk analysis to better support safety management.

Overall, the results provided a comprehensive research synthesis and analysis, augmenting knowledge on the role of BIM in construction safety. Hence, the study output can be considered a reference framework to enhance construction workers' safety by means of new technologies, which can play a fundamental role for developing "Safety 4.0" in the construction industry.

In addition, the use of BIM solutions for OHS can go beyond the analyzed sector as the output of this research can be used for future studies to extend the knowledge on their implementation in other contexts. The latter consideration of the authors is also referred to the worldwide emergency due to the Coronavirus (Covid-19), since, currently, in most workplaces (not only in the construction industry), the related flows of operators and setting of working distances need to be redesigned to reduce infection risks. Hence, the novel safety measures against this biological hazard can certainly take advantage of BIM applications and models developed in the construction industry.

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## Appendix A

In Table A1 the list of the selected documents is provided.

**Table A1.** List of the selected documents grouped per each trend in alphabetical order.

Ref.	Author	Year	Journal	Country	Trend
[49]	Deng et al.	2019	Advances in Civil Engineering	China	T.1
[46]	Ding et al.	2016	Safety Science	China	T.1
[54]	Hallowell et al.	2016	Construction Innovation	USA	T.1
[47]	Hossain et al.	2018	Automation in Construction	Singapore	T.1
[45]	Jin et al.	2019	Engineering, Construction, and Architectural Management	USA	T.1
[52]	Kim et al.	2015	Journal of Computing in Civil Engineering	South Korea	T.1
[48]	Mihic et al.	2018	Tehnicki Vjesnik	Croatia	T.1
[53]	Shen and Marks	2016	Journal of Construction Engineering and Management	USA	T.1
[44]	Yuan et al.	2019	Automation in Construction	China	T.1

Table A1. Cont.

Ref.	Author	Year	Journal	Country	Trend
[51]	Zhang et al.	2016	Journal of Civil Engineering and Management	China	T.1
[50]	Zou et al.	2016	Engineering, Construction, and Architectural Management	U.K.	T.1
[29]	Zou et al.	2017	Safety Science	U.K.	T.1
[69]	Hara et al.	2019	Advances in Computational Design	Japan	T.2
[58]	Hossain and Ahmed	2019	International Journal of Construction Management	Bangladesh	T.2
[68]	Ji and Leite	2018	Automation in Construction	USA	T.2
[64]	Khan et al.	2019	Advances in Civil Engineering	South Korea	T.2
[70]	Kim and Teizer	2014	Advanced Engineering Informatics	USA	T.2
[71]	Kim et al.	2015	Journal of computing in Civil engineering	USA	T.2
[72]	Li et al.	2018	Automation in Construction	China	T.2
[56]	Lin et al.	2017	Engineering, Construction, and Architectural Management	Singapore	T.2
[63]	Luo and Gong	2015	Journal of Intelligent and Robotic Systems	China	T.2
[61]	Malekitabar et al.	2016	Safety Science	Iran	T.2
[66]	Melzner et al.	2013	Construction Management and Economics	Germany	T.2
[57]	Park and Kim	2015	International Journal of Architectural Research	South Korea	T.2
[65]	Qi et al.	2014	Journal of computing in engineering	China	T.2
[73]	Sadeghi et al.	2016	Journal Technology	Iran	T.2
[59]	Schwabe et al.	2019	Automation in Construction	Germany	T.2
[55]	Teo et al.	2016	Construction Economics and Building	Singapore	T.2
[72]	Wang et al.	2015	Automation in Construction	USA	T.2
[60]	Zhang et al.	2015	Automation in Construction	USA	T.2
[67]	Zhang et al.	2015	Safety Science	USA	T.2
[15]	Zhang et al.	2013	Automation in Construction	USA	T.2
[83]	Abed et al.	2019	Civil Engineering Journal	IRAQ	T.3
[75]	Kim et al.	2019	Applied Sciences	USA	T.3
[74]	Kim et al.	2016	Automation in Construction	USA	T.3
[77]	Kim et al.	2018	Journal of Management in Engineering	USA	T.3
[78]	Kim et al.	2018	Journal of Construction Engineering and Management	USA	T.3
[76]	Kim et al.	2016	Automation in Construction	USA	T.3
[82]	Marzouk and Daour	2018	Safety Science	Egypt	T.3
[79]	Moon et al.	2014	Automation in Construction	South Korea	T.3
[80]	Moon et al.	2014	Advanced Engineering Informatics	South Korea	T.3
[81]	Xie et al.	2011	Electronic Journal of Information Technology in Construction	USA	T.3
[91]	Al Hattab et al.	2018	Construction Innovation	Lebanon	T.4
[87]	Arslan et al.	2019	Personal and Ubiquitous Computing	France	T.4
[86]	Hu and Zhang	2011	Automation in Construction	China	T.4
[90]	Lee et al.	2012	Automation in Construction	South Korea	T.4
[84]	Tixier et al.	2017	Automation in Construction	France	T.4
[89]	Yi et al.	2015	Journal of Mechanical Engineering Research and Developments	China	T.4
[85]	Zhang and Hu	2011	Automation in Construction	China	T.4
[88]	Zhang et al.	2015	Automation in Construction	USA	T.4
[104]	Akula et al.	2013	Automation in Construction	USA	T.5
[97]	Arslan et al.	2019	Automation in Construction	France	T.5
[95]	Arslan et al.	2014	Journal of Information Technology in Construction	Pakistan	T.5
[105]	Cheung et al.	2018	Sensors	Taiwan	T.5
[92]	Choe and Leite	2017	Automation in Construction	South Korea	T.5
[96]	Costin et al.	2015	Journal of Information Technology in Construction	USA	T.5
[108]	Forsythe P.	2014	Proceedings of Institution of Civil Engineers: Management, Procurement, and Law	Australia	T.5
[103]	Golovina et al.	2019	Automation in Construction	Germany	T.5
[102]	Golovina et al.	2016	Automation in Construction	Germany	T.5
[99]	Li et al.	2018	Safety Science	China	T.5
[100]	Park et al.	2017	Journal of Construction Engineering and Management	USA	T.5
[107]	Park et al.	2017	Advanced Engineering Informatics	USA	T.5
[94]	Riaz et al.	2017	Journal of Engineering, Design, and Technology	Pakistan	T.5
[93]	Riaz et al.	2014	Automation in Construction	Pakistan	T.5
[106]	Smaoui et al.	2018	Sensors and materials	USA	T.5
[98]	Tagliabue et al.	2018	In_bo	Italy	T.5
[101]	Wu et al.	2015	Visualization in Engineering	Taiwan	T.5
[110]	Clevenger et al.	2015	Advances in Engineering Education	USA	T.6
[30]	Getuli et al.	2018	In_bo	Italy	T.6
[112]	Li et al.	2015	Automation in Construction	Hong Kong	T.6
[111]	Liu et al.	2017	ICIC Express Letters, Part B: Applications	Taiwan	T.6
[109]	Park and Kim	2013	Automation in Construction	South Korea	T.6
[27]	Alomari et al.	2017	Safety	USA	T.7
[115]	Enshassi et al.	2016	International Journal of Construction Management	Palestine	T.7
[118]	Ganah and John	2017	Journal of Engineering, Design, and Technology	U.K.	T.7

Table A1. Cont.

Ref.	Author	Year	Journal	Country	Trend
[26]	Ganah and John	2015	Safety and Health at Work	U.K.	T.7
[113]	Marefat et al.	2019	Engineering, Construction, and Architectural Management	Iran	T.7
[114]	Swallow and Zulu	2019	Frontiers in Built Environment	U.K.	T.7
[117]	Swallow, M., Zulu, S.	2019	Journal of Engineering, Design, and Technology	U.K.	T.7
[116]	Zulkifli et al.	2016	Journal Technology	Malaysia	T.7
[122]	Arslan et al.	2019	Safety Science	France	T.8
[119]	Dong et al.	2018	Safety Science	China	T.8
[121]	Lee et al.	2019	KSCE Journal of Civil Engineering	China	T.8
[120]	Li et al.	2015	Safety Science	Hong Kong	T.8
[124]	Olugboyege and Windapo	2019	Frontiers in Built Environment	South Africa	T.8
[123]	Shuang et al.	2019	Safety Science	China	T.8

**Legend:** T.1—Knowledge-based systems; T.2—Automatic rule checking; T.3—Scheduling information; T.4—Overlapping and clash detection; T.5—Proactive feedback; T.6—Training; T.7—Stakeholders' perception; T.8—Workers' behavior.

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