EXAMINING BIM-BASED AUTOMATED RULE-CHECKING TECHNIQUES IN CONSTRUCTION

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Abstract

Research and Experimentation prove that construction safety planning and preparation during the Design phase significantly impact the safety of the construction workers. Construction work is an extensive and intense process consisting of several stages and activities that run simultaneously. The nature of the construction activities is dangerous and risky. Hence, construction workers' health and safety are threatened. However, previous studies claim that Designers and Architects are more concerned with the aesthetics of the building than with safety issues. In addition, they often lack construction safety knowledge, which is essential to effectively mitigate or reduce construction risks through design. This short review examines the Automated Rule checking tools that mainly assist in design for safety or Prevention Through Design (PtD) using BIM to oversee and mitigate construction risks during the construction phase. Based on a systematic review related to BIM-based health and safety practices, and after filtering the 99 collected articles, 19 articles related to Automated Rule checking were included in this short review. Findings suggest that the primary approach to preventing construction risks through design is creating an automated safety rule-based knowledge library for designers to automatically check the BIM models for specific safety risks. Moreover, assisting in construction safety planning and explaining the construction risks to designers and architects.

Keywords: Automated Rule checking; Construction Health and Safety; Prevention Through Design (PtD); Design for Safety; Building Information Modelling (BIM).

1. INTRODUCTION

Persistent health and safety procedures are applied to avoid construction accidents in the AECO (Architectural, Engineering, Construction and Operation) sector. Nevertheless, construction labour has the most serious accident and death rates among other sectors (Ahn et al., 2020).

In 2019, Occupational Safety and Health Administration (OSHA) registered around 200 thousand injuries related to construction work (Labor, 2019). The AECO sector is responsible for 9.5 fatalities per hundred thousand full-time workers. Similarly, one in five worker fatalities was in the AECO sector (Labor, 2019). According to the U.S. Department of Labour, Bureau of Labour statistics, the major causes of accidents and injuries are stuck-in, falls, struck-by-objects, and electrocution. These causes were responsible 2019 for 58.6% of the deaths of AECO workers (Labour, 2019). Furthermore, fatalities related to falls, slips, and trips increased from 805 in 2020 to 850 in 2021, representing a 5.6% increase in 2021 in all industries. The construction sector accounted for 370 of these fatalities in 2021, an increase of 7.2% from 2020, when there were 345 fatalities (Labour, 2022). Construction-related work is responsible for 951 fatalities in 2021 in the U.S., considered the second most occupational death in 2021 (Labour, 2022).

According to Wang's accident causations theory, five accident causations factors are responsible for accidents occurrence (Wang, 2018). These causation factors are Personal factors, Unsafe actions, Environment and Heredity, Management, Job factors, and conditions. Thus, organisation members must have safe environments and implement safety knowledge based on specific and detailed safety training to avoid risky behaviours before on-site construction. Moreover, the work site should constantly be supervised and monitored to prevent accidents (Wang, 2018).

The traditional safety approaches depend on manual supervision and monitoring. Hence, traditional approaches incorporate a lot of human errors and misjudgement (Eleftheriadis et al., 2017). There is an urgent need to shift to more digitalised and automatised prevention methods to overcome these traditional approaches that most construction industry still relies on (Zhou et al., 2015). Building Information Modelling (BIM) is one of the most promising tools being heavily investigated and implemented. BIM approaches, along with different contributions to the AECO sector, have the ability to assist in the automation of the safety management and coordination of the AECO sector (Eleftheriadis et al., 2017). Other research areas involving BIM for safety in the AECO sector are the usage of BIM in safety education and training (Clevenger et al., 2015). BIM for visualisation may facilitate the worker's and the student's skills to understand and identify construction concepts (Sidani, Dinis, et al., 2021; Sidani, Matoseiro Dinis, et al., 2021). Alongside safety automation, visualisation, training and education, BIM tools are widely utilised in various safety fields in the AECO, such as safety planning, monitoring, design for safety, safety inspection, and safety at the facility and management phase (Clevenger et al., 2015).

This review examines the present investigation in the field of BIM-based construction safety and Automated Rule Checking. Consequently, answering six essential questions provides an overview of the current interventions, objectives, targeted risks, targeted groups, hardware and software, assessment methods, standards, and regulations utilised to develop BIM-based Automated Rule Checking applications for safety in construction. The questions are as follows:

1. What are the main target groups?
2. What are the major risks being targeted by the BIM-based Automated Rule checking?
3. At which stage of the Project life cycle is the BIM-based Automated Rule checking implemented?
4. Which standards and regulations are being followed?
5. What tools and programs are used to fulfil the requirements of the intervention?
6. What are the limitations of BIM-based Automated Rule checking?

2. METHODOLOGY

The current review is based on a systematic review of BIM-based solutions for construction health and safety. The systematic review was performed with the leading electronic databases for scientific literature in multidisciplinary, construction and safety areas. The search underwent a snowballing technique examining the articles' references to investigate relevant studies from another electronic database that were not gathered during the search (Wohlin, 2014). Three keywords were used for the search: ("Construction, Occupational Health and Safety, and Building Information Modelling"). Furthermore, the authors considered the alternative expressions of each keyword, such as work health and safety, risks, accidents, and BIM.

After collecting the articles, the second step of the systematic review was screening the articles. Afterwards, the authors excluded conferences, reviews, discussions, and unpublished articles based on well-structured inclusion and exclusion criteria. Likewise, Studies not related to the AECO sector were rejected. 99 articles were considered adequate for the review, among which 19 articles targeted the fields of Automated Rule Checking for construction safety. Figure 1 mentions the number of fields each article targeted, considering that some articles mentioned more than one field totalling 129 fields targeted by the 99 articles. The search was performed in 2022, and the articles collected were up until August 2022. The authors did not consider any initial date.

The following sections demonstrate the results of the collected articles. All the listed questions are addressed following a discussion of the main findings, limitations, and the most promising tools to be considered, conclusions and future considerations.

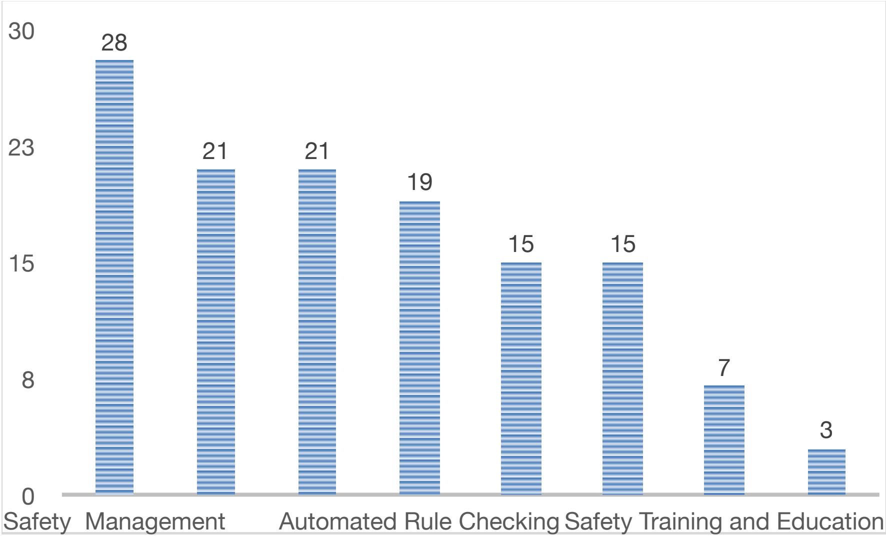

Figure 1. *Literature review results: Number of mentions for Safety Fields*

3. RESULTS

In order to facilitate the organisation of the information obtained from the 19 collected articles in the field of automation rule checking, the results will be categorised based on the six questions mentioned earlier.

3.1. Main Target Groups

The three main target groups that the authors focused on in their interventions are presented in Fig.2: Safety managers, with 11 mentions (Ji & Leite, 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Malekitabar et al., 2016; Shen & Marks, 2016a; Wang et al., 2015; Yang et al., 2022; S. Zhang et al., 2013; S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015), Designers/Architects with ten mentions (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018; Khan et al., 2019; Lu et al., 2021; Rodrigues et al., 2021; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021), and finally construction managers with three mentions only (Kim et al., 2018; B. Li et al., 2022; Y. Zhang et al., 2021). It is important to note that the final number is 24 mentions. Some articles focused on more than one target group. Also, some articles mentioned designers, and others referred to them as Architects in order to generalise the naming of the authors referred to them as Designers/Architects.

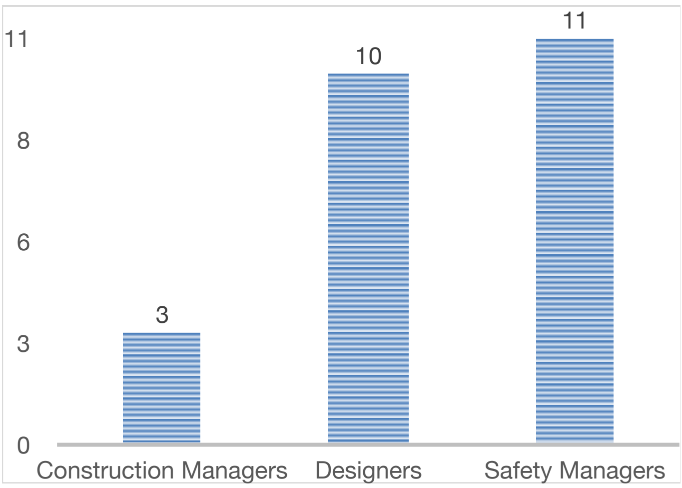

Figure 2. *Target Groups*

3.2. Major risks

Automated Rule Checking collected articles focused on ten major risks Fig.3. The articles represented the risks differently. Some mentioned work-related risks such as excavation, roofers, carpenters, and masonry work. Others mentioned risks related to machinery and tools such as cranes, scaffolding, or other heavy machinery. The rest mentioned risks, such as falls, electrocution, being caught in between, and caved in, among others. The authors of this paper merged some of the risks of the same nature. For example, excavation and underground-related risks are considered the same as caught in between, caved in, and risks resulting in working in confined spaces. Similarly, scaffolding-related work was considered as falls. The highest number of mentions occurs for Falls, with nine (M. M. Hossain & Ahmed, 2019; Kim et al., 2018; B. Li et al., 2022; Malekitabar et al., 2016; Rodrigues et al., 2021; Wang et al., 2015; Yang et al., 2022; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015); following was excavation and underground related work with five mentions (Khan et al., 2019; M. Li et al., 2018; Malekitabar et al., 2016; Wang et al., 2015; Y. Zhang et al., 2021); general construction site risks were mentioned twice (M. A. Hossain et al., 2018; Yuan et al., 2019), and the rest of the risks were mentioned only once. It is worth mentioning that various articles targeted several risks, resulting in a total of 27 risks.

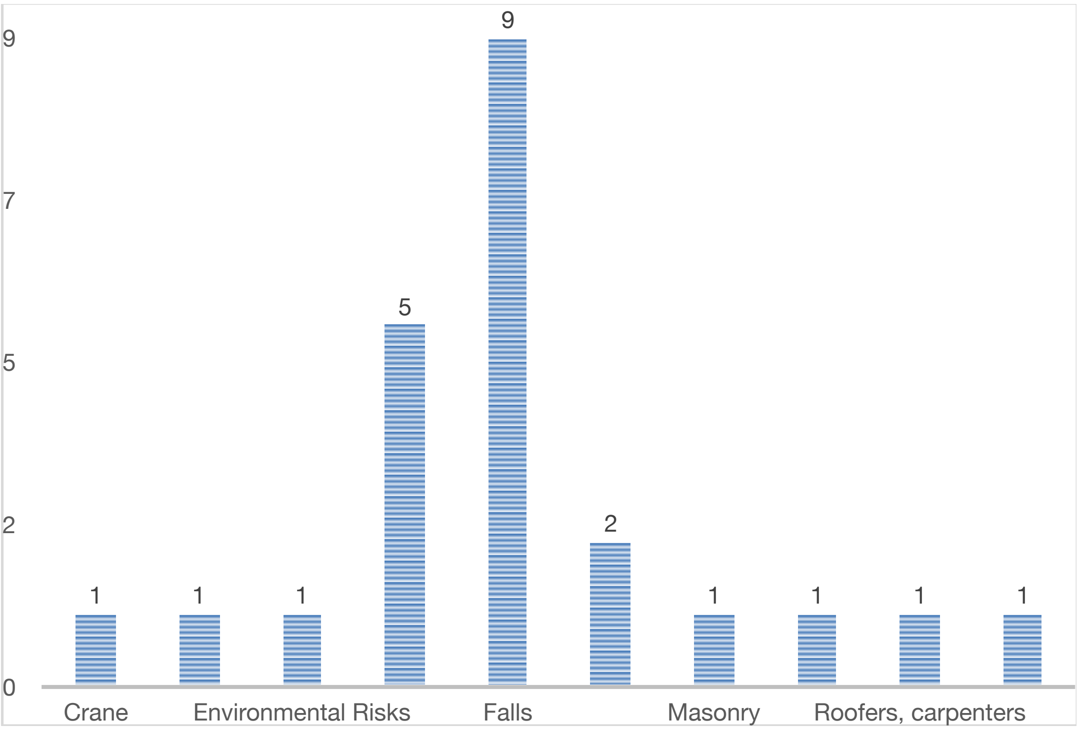

Figure 3. *Major Targeted Risks*

3.3. Construction phase

Only three construction phases were mentioned (Fig.4). The majority implemented in the Design Phase with nine mentions (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Lu et al., 2021; Malekitabar et al., 2016; Rodrigues et al., 2021; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021), Pre-construction with six mentions (Ji & Leite, 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Wang et al., 2015; Y. Zhang et al., 2021), and the construction phase with five mentions (B. Li et al., 2022; Shen & Marks, 2016b; Yang et al., 2022; S. Zhang, Boukamp, et al., 2015; Y. Zhang et al., 2021).

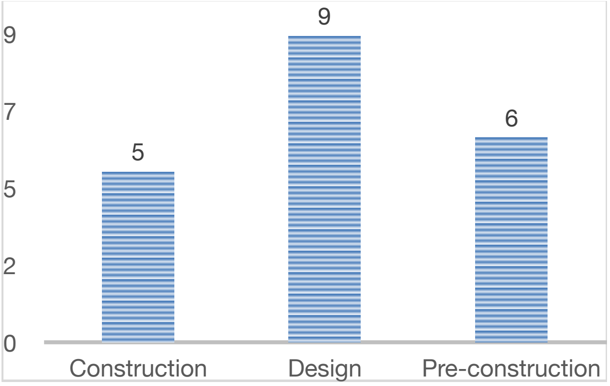

Figure 4. *Construction Phases*

3.4. Standards and Regulations

Only 14 out of the 19 collected articles mentioned standards and regulations that their work was based on, as shown in Table 1. Most authors implemented OSHA regulations or national/local regulations. Some authors used specific parts of OSHA. For example, Ji based their work on ASME B30.3- 2016 Edition “Tower Cranes” (Ji & Leite, 2018). While other others referred to OSHA for best practices (Rodrigues et al., 2021; Wang et al., 2015; S. Zhang, Boukamp, et al., 2015). Tab.1 summarises the results.

Table 1. *Standards and Regulations*

Article Title	Standards and Regulations
Construction safety risk drivers: A BIM approach	• OSHA - The National Institute of Occupational Safety and Health (NIOSH) has conducted a study on Fatal Accident Circumstances and Epidemiology (FACE) • OSHA comprises 70 ‘‘fatal facts” that fall in the category of construction accidents Iran’s safety code • International Risk Governance Council (IRGC),
Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modelling	OSHA - Standards and industrial best practices OSHA 1926.652 (a)(1)
Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking	OSHA - **ASME B30.3- 2016 Edition** “Tower Cranes” and Occupational Safety and Health Administration (OSHA) electronic code of federal regulations **(e-CFR) Title 29, Part 1926**, Subpart CC – “Cranes & Derricks in Construction.”
BIM-based fall hazard identification and prevention in construction safety planning	OSHA
Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	• OSHA • Construction Industry Best Practices” • Construction Safety Alliance - Examining Causes of Construction Injuries and Defining Best Practices That Improve Safety Performance, Construction Information Quarterly, Chartered Institute of Building, Ascot, U.K., 2004”
Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	• OSHA - regulations and industry safety best practices • OSHA regulation 1926, • The Occupational Injury and Illness ClassificationManual, and Construction Solutions Database.
Excavation Safety Modeling Approach Using BIM and VPL	OSHA
Safety plugins for risks prevention through design resourcing BIM	• OSHA - Occupational Safety and Health Administration and good practices guidelines • Portuguese safety legal regulations (DL273/2003 and DL 41821/1958) and the OSHA 1926–501 (2019). • Regulation no. 101/96 of April 3 (Portaria no. 101/1996)
An automated safety risk recognition mechanism for underground construction at the pre-construction stage based on BIM	• Guidelines for tunnelling risk management • Assessment of the Safety of Tunnels” construction technical manuals
Design-for-Safety knowledge library for BIM-integrated safety risk reviews	Building Regulation in the UK
BIM-integrated construction safety risk assessment at the design stage of building projects	• BLS Injuries, Illnesses, and Fatalities (IIF) program • Census of Fatal Occupational Injuries (CFOI) of the IIF program • Survey of Occupational Injury and Illness (SOII) of the IIF program • 2010 Standard Occupational Classification (SOC) system • BLS Occupational Employment Statistics (OES • RSMeans Data
Towards a unifying domain model of construction safety, health and well-being: SafeConDM	BG Bau 100 regulation
Developing an automated safety checking system using BIM: a case study in the Bangladeshi construction	• Bangladesh National Building Code (BNBC-2006) • Bangladesh Labor Acts (BLA- 2006),
Accident prevention through design (PtD): Integration of building information modeling and PtD knowledge base	• Mandatory provisions of project construction standards (building construction part) • The standard for safety inspection of building construction” in China, • Safety regulations, documents, and best practices

3.5. Hardware, software, and Data Exchange Formats

Most articles listed the BIM software used, the languages in which they created the algorithms or risk databases, and the Model checker programs. In addition, the authors listed the data exchange format used. Table 2 summarises the hardware, software and data exchange formats employed or developed by the authors and the file formats that the authors adopted.

Table 2. *Hardware, Software and Data Exchange Formats*

Title	Tools
Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling (Wang et al., 2015)	• Algorithms were developed in Matlab™ • Commercially available terrestrial laser scanner • GIS
A BIM-based identification and classification method of environmental risks in the design of Beijing subway (Zhou et al., 2021)	• Autodesk Revit • Safety evacuation design toolbox (SEDT) • 3Dmax • Navisworks • 3D GIS Engine "Citymaker Server V7.0." • FDB (feature database)
Automated tower crane planning: leveraging 4-dimensional BIM and rule-based checking (Ji & Leite, 2018)	• Autodesk Revit • Microsoft Excel • Solibri Model Checker v9.7 (SMC) • IFC data exchange format
Towards a unifying domain model of construction safety, health and well-being: SafeConDM (B. Li et al., 2022)	• Autodesk Revit • Graphisoft Archi- CAD • IFC data exchange format
Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA) (S. Zhang, Boukamp, et al., 2015)	• The SemanticWeb Rule Language (SWRL) • IFC data exchange format
Accident prevention through design (PtD): Integration of building information modeling and PtD knowledge base (Yuan et al., 2019)	• Autodesk Revit • Microsoft Access is used to create a PtD knowledge base for safety risks related to design, laying the foundation for the automatic detection of PtD. • Microsoft Visual C# • A plug-in based on Revit was developed in this research to implement the automatic inspection of rules,
Design-for-Safety knowledge library for BIM-integrated safety risk reviews (M. A. Hossain et al., 2018)	• Microsoft's C# (build the DfS rule-based knowledge library) • Reasoning Engine reads BIM-compliant digital models in IFC format and comprises a set of safety-checking algorithms. • MySQL • IFC data exchange format
BIM-integrated construction safety risk assessment at the design stage of building projects (Lu et al., 2021)	• Autodesk Revit 2018 plugin was created • Revit API to develop Windows Presentation Foundation, • C# language for further development based on Microsoft Visual Studio 2017.
Safety plugins for risks prevention through design resourcing BIM (Rodrigues et al., 2021)	• Revit API, "Job Hazard Analysis" (JHA) plugin developed, • C# language • "SafeObject" plugin
Semantic IFC data model for automatic safety risk identification in deep excavation projects (Y. Zhang et al., 2021)	• Autodesk Revit • ArchiCAD • Construction Risk Identification System (CRIS) Prototype
Developing an automated safety checking system using BIM: a case study in the Bangladeshi construction industry (M. M. Hossain & Ahmed, 2019)	• Autodesk Revit • Solibri Model Checker (SMC 2014). • IFC data exchange format
Near-Miss Information Visualization Tool in BIM for Construction Safety (Shen & Marks, 2016a)	• Autodesk Revit • Open application programming interface (API)

An automated safety risk recognition mechanism for underground construction at the pre-construction stage based on BIM (M. Li et al., 2018)	• SPSS20.0 software for cluster analysis • SQL database software is used to store the safety risk knowledge • BIMQL, which is an open query language for building information models, combines • IFC standard database with the BIM-cloud by designing a set of query systems. • Backus-Naur Form method, engineering information in the BIM models can be well read in the BIM platform
Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules (S. Zhang et al., 2013)	• Tekla Structures
BIM-based fall hazard identification and prevention in construction safety planning (S. Zhang, Sulankivi, et al., 2015)	• Tekla Structures that incorporate the safety rule-checking algorithms • IFC data exchange format
BIM-Driven Automated Decision Support System for Safety Planning of Temporary Structures (Kim et al., 2018)	• A decision-making engine was created to support decision-making for scaffolding. • Created Simulation Engine
Excavation Safety Modeling Approach Using BIM and VPL (Khan et al., 2019)	• Autodesk Revit • Visual programming language (VPL) • Hummingbird • Rhino - Grasshopper (plug-in)

3.6. Limitations of Automated Rule Checking

Limitations can be classified into six categories. The first category refers to limitations related to the BIM models. In general, the models need to be developed to a relatively high maturity stage. In addition, models often contain inaccurate, incomplete or incorrect information, need to be more automated to reduce the manual efforts needed for modelling work and scheduling, require more safety design elements and natural constraints of the construction sites still cannot be accurately modelled, thus, lacking the realism of construction sites (M. A. Hossain et al., 2018; M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018; Khan et al., 2019; Malekitabar et al., 2016; Shen & Marks, 2016a; Yuan et al., 2019; S. Zhang et al., 2013; S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015; Zhou et al., 2021).

The second category refers to safety risks-related limitations. The databases and libraries for risks are lacking. Most authors targeted one or few risks because they could not access extensive safety databases. In addition, automation of risk detection should be increased for multiple scenarios and needs to include environmental and spatial analysis. Similarly, the detection of dynamic safety hazards is missing. Still, manual efforts are needed to contextualise safety rules into computer language and complex and complete algorithms to refine safety risks are required. Model checkers still lack the integration of safety regulations and standards (M. A. Hossain et al., 2018; M. Li et al., 2018; Rodrigues et al., 2021; Wang et al., 2015; S. Zhang et al., 2013; Zhou et al., 2021).

As a third category, there are limitations related to the case studies. These are mostly related to one risk in a single construction site or a controlled environment. More complex case studies should be done with more risks and a variety of construction site typologies (M. M. Hossain & Ahmed, 2019; B. Li et al., 2022; Malekitabar et al., 2016; Wang et al., 2015; S. Zhang et al., 2013; S. Zhang, Sulankivi, et al., 2015).

The fourth category includes limitations related to the steep learning curve of implementing Automated Rule Checking tools and procedures. Not all personnel involved in the construction work have the same educational level, modelling experience, or using digital tools. Thus, Automation Rule Checking makes it very difficult for some workers to understand and extract the required information. Visualisation of the Automated Rule Checking information is also considered a limitation, and there is a need to introduce immersive tools in order to facilitate training, education, and visualisation (M. M. Hossain & Ahmed, 2019; Khan et al., 2019; Shen & Marks, 2016a).

The fifth category refers to limitations that result from the interoperability of the file exchange formats. Most of the authors used IFC as the preferred data exchange format. Nevertheless, IFC presented interoperability issues. Moreover, IFC needs to be expanded to target more risk types (S. Zhang, Boukamp, et al., 2015; S. Zhang, Sulankivi, et al., 2015; Y. Zhang et al., 2021).

The sixth and final category includes limitations related to Standards and regulations. Most of the authors were able to verify models for compliance with some of the regulations related to construction safety. However, most of the rules are not verifiable due to limitations in available software tools, modelling development practices or in the nature of the rules themselves (M. M. Hossain & Ahmed, 2019; Yuan et al., 2019; S. Zhang et al., 2013).

4. DISCUSSIONS

Designers and Safety Managers were mentioned in 21 out of 24 by the authors, leaving Construction Managers with only three mentions, as shown in Fig. 2. This shows a clear trend favouring Architects/ Designers and Safety Managers before construction works. Moreover, the Pre-construction and Design phases were mentioned 15 times out of 20, and the Automated Rule Checking tools were used only five times during the construction phase.

Several articles did not contain any reference for regulations, standards, or best practices. The OSHA regulations had ten mentions. Precisely, the authors selected specific chapters and topics to include in their work.

The most mentioned BIM modelling tool was Autodesk Revit, with ten mentions, while Tekla structure and ArchiCAD were less common and were mentioned twice and once, respectively.

Considering Rule checking programs, Solibri Model Checker was mentioned twice (M. M. Hossain & Ahmed, 2019; Ji & Leite, 2018). Six authors created different model-checking tools (M. A. Hossain et al., 2018; Khan et al., 2019; Kim et al., 2018; M. Li et al., 2018; Y. Zhang et al., 2021; Zhou et al., 2021). Five authors created plugins (Lu et al., 2021; Rodrigues et al., 2021; Shen & Marks, 2016a; Yuan et al., 2019; S. Zhang, Sulankivi, et al., 2015), as described in Table 2.

Regarding Data Exchange Format, the authors mentioned IFC the most, with almost no other Data exchange format mentioned, as shown in Table 2.

5. CONCLUSION

Automated Rule Checking seems a promising approach to improve safety levels in construction. Investigation in this field is currently expanding, and more model-checking tools, safety libraries, databases, and best practices are being created, facilitating the execution of Automated Rule Checking techniques. Furthermore, standards, regulations and best practices are being translated into computer languages, enabling the implementation of more risks. It is believed that the advancement of Artificial Intelligence automated Rule checking for safety will involve more risks that are hard to translate to machine languages.

Automated Rule checking still faces some limitations. First, the environment of construction sites is constantly changing, so it may not be possible to automatically check all unsafe conditions in a BIM model in real-time. Moreover, manual effort in rule interpretation is still required for rule translation into machine-readable code. Furthermore, there is still a lack of safety and risks databases regarding modelling, reports, best practices, and algorithms. More immersive training and visualisation tools are required to assist with the steep learning curve and enable construction workers to clearly understand the models, risks, and prevention methods. The interoperability issue of IFC is improving, but it is still necessary to incorporate safety risks. Finally, standards and regulations should be modified to facilitate the adaptation to computer language.

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