



A BIM for safety Framework Involving Automated Rule Checking, Visualization and Training

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Abstract

The construction industry bears a lot of casualties and accidents more than other high-risk industries annually. Thus, to have a practical site inspection, monitoring, and training, the AECO (Architecture, Engineering, Construction, and operation) is gradually integrating new digital technologies such as building information modelling (BIM), automatic rule checking, Augmented and Virtual Reality (AR/VR).

The current research objective is to provide a general framework of a BIM-based safety system to improve the safety status in the construction field. The system aims to offer Safety planning, Visualization, safety management, training, automated rule checking, monitoring and inspection. A BIM for Safety verification system is proposed, based on a fully automated approach, adopting Automated rule checking, and a manual approach adopting Virtual and Augmented Reality (AR/VR). These two systems will be a part of a BIM for Safety General Framework, which covers the construction project lifecycle with all the involved stakeholders and international standards.

The BIM-based technologies can help with safety prevention, inspection, monitoring, and training from the design stage to the operation and management. The integration of these tools in a standardised manner could ease the adoption of the tools, following EN ISO 19650-1 and PAS 1192-6:2018, giving the owner better awareness and control over the safety aspects of the project, identifying specific tasks for each stakeholder, and involving health and safety measures from the beginning of the project. Some limitations are found in implementing new tools since every tool represents a standalone, each tool covers a specific field only, the digital tools are not involved in the standards and regulations, workers and safety professionals lack the experience of using such tools, low demand from the owners, incompatibility of software and data format exchange, especially between different appointed parties, and the time spent preparing the BIM model.

Keywords. Building Information Modelling, Automated Rule Checking, Augmented Reality, Virtual Reality, Construction, Occupational Health and Safety.

Introduction

Construction safety is an international concern, with many injuries occurring in construction sites worldwide (Zhang, Teizer, Lee, Eastman, & Venugopal, 2013a). In line with the Occupational Safety and Health Administration (OSHA), the construction industry was responsible for 199,200 injuries and illnesses in 2019. According to the U.S. Bureau of Labour Statistics, construction had 9.5 fatalities per 100,000 full-time workers (U.S. Department of Labor; Bureau of Labor Statistics, 2019). According to OSHA, as of 2020, "one in five worker deaths in 2019 in construction".

Falls, struck-by-objects, electrocution, and stuck-in are considered the fatal four construction accidents and were responsible for more than half of the construction workers deaths at 58.6% in 2020 (U.S. Department of Labor; Bureau of Labor Statistics, 2019).

In a study conducted by Chim on the Causes and Preventive Approaches to Mitigate Accident Rate, Chim reassured that the company and the workers' negligence is the leading cause for accidents on



the construction site (Chim, Chun, & Wah, 2018). Chim mentioned that accidents could be avoided if the construction company management is careful with supervision during the construction process. According to Abdelhamid and Everett, three factors trigger accidents: not identifying a dangerous situation related to a specific task, ignoring a hazardous condition, and proceeding with the activity, or acting unsafe whatever the current environment was (Abdelhamid & Everett, 2000). In a book published by the Health and Safety Executive, the authors explored several points such as the influence of the human's behaviour on health and safety, the impact that health and safety problems have on the worker's physical and mental health, and the book also illustrates how to identify and solve these issues (Health and Safety Executive, 1999). This book states that a thoughtful understanding of human actions at work can reduce the number of accidents and cases of occupational hazards. Unsafe human on-site actions cause at least 80% of accidents since people are involved during the whole construction lifecycle. The authors divided the human factors into violations and errors that are further divided into skill-based errors and common mistakes (Health and Safety Executive, 1999).

Moreover, the causes of the issues are related to the organisation's planning, management and decision-making functions. The authors suggested having planned construction and maintenance tasks and an organized site environment with workplace precautions, risk control systems, and management arrangements to assist with safer construction works. In addition, the skills, capabilities and mental health of the individuals should be assessed for each task (Health and Safety Executive, 1999).

Thus, the construction site requires regular and advanced monitoring and supervision; besides, new workers must be trained carefully before going to the construction site to avoid unsafe actions. Consequently, manual monitoring and supervisions are prone to error due to the complex and dynamic environment. Subsequently, to assist the supervisors and visual inspection of the risks, automated safety monitoring such as Building Information Modelling (BIM) is adopted by the AECO sector (Eleftheriadis, Mumovic, & Greening, 2017). BIM integrates Building Regulations and health and safety information within the model that are specified as BIM4REGS task group. These groups have been developed by representatives from the AECO sectors, all with a common goal in developing and improving awareness, skill, and the use of BIM. The health and safety group aims to incorporate health and safety requirements into BIM so that users can immediately see whether their designs are compliant (Mordue & Finch, 2019). Therefore, BIM implementation seems promising and can also assist the continuous advancements in the construction processes. Furthermore, BIM can provide essential decision-support tools for engineers throughout the design stage, improving workers' safety and performance and enriching on-site and off-site training (Wang & Chong, 2015).

Digital Technologies for Construction Safety

BIM application in the AECO sector

BIM application in the AECO sector has several benefits, such as reducing health and safety challenges, improving the project's quality, and enhancing collaboration (Enshassi, Ayyash, & Choudhry, 2016). There is significant interest in improving safety through design and work method using BIM by implementing safety planning throughout the project (Enshassi et al., 2016). BIM enables workers, safety specialists and engineers to digitally visualise and monitor construction sites and identify hazards (Azhar, Khalfan, & Maqsood, 2012; Enshassi et al., 2016). Consequently, with the advancement of BIM and the lifecycle realisation of the project in one holistic environment, most of the Health and Safety information can be generated in this single environment (Kim, Jeong, Clayton, Haberl, & Yan, 2015; Schwegler, 2010). Furthermore, 4D-BIM, which is 3D models plus schedule, means improved chances to make alternative preliminary plans of different construction stages and tasks, linking them more to safety (Ganah & John, 2015).

The AECO sector is recognised for its increasing complexity and competitiveness due to strict schedules, complex tasks, and limited budgets, driving the search for automated and technological solutions (Chan, Scott, & Chan, 2004; Pham, Pedro, Le, Lee, & Park, 2017). Digitalisation has offered



this sector the means to pursue higher performance and accuracy, thus reducing costs and modernising operations. Implementing BIM methodology has benefited the AECO sector in collaboration, scheduling, 3D drawings, management, quantity, and material sorting. Consequently, various countries are adopting BIM. For European countries, BIM adoption is reinforced by Directive 2014/E.U., Article 22 (European Commission, 2014), which refer to BIM application for public procurement and by the modern international standard for BIM EN ISO 19650-1 (BS EN ISO 19650-1, 2018). The AECO sector is currently implementing several tools and methodologies to assist BIM, such as Automated Rule checking, Augmented Reality (AR), Virtual Reality (VR) (Sidani, Dinis, et al., 2021; Sidani, Matoseiro Dinis, et al., 2021).

Fully Automated Verification Systems (Rule Checking)

Rule-based checking systems have been developed for BIM models as part of the new BIM technology 3D and 4D simulations, which means a mockup of the geometric model (3D) and a geometric model with schedule details (4D), to improve the understanding of construction operation. These are some of the features embedded in BIM, allowing effective safety planning throughout the project's lifecycle (Eastman, Lee, Jeong, & Lee, 2009). In addition, such technologies can improve health and safety through automated risk identification at an earlier stage and propose inexpensive and straightforward ways to solve unsafe situations.

According to Sijie Zhang, collecting and examining construction data (work breakdown, structure, schedules, resource allocation) can be linked to a BIM model allowing to generate a rule-based health and safety framework that facilitates safer design, planning and execution of work tasks (Zhang, Teizer, Lee, Eastman, & Venugopal, 2013b). In addition, joining the construction data with safety rules, such as OSHA, and geometric project data can create information that, once the database is linked to the BIM model, will create knowledge that can enhance safety education and training at the design and construction stage (Zhang et al., 2013b).

Safety standards and codes represent guidelines for construction risk identification. Therefore, it is convenient to link BIM components or activities with relevant safety regulations and codes to carry out automatic risk identification. According to Guo Hongling (Hongling, Yantao, Weisheng, & Yan, 2016a), a safety rule system is thus built by:

- Categorising construction safety information,
- Building a safety rule system
- Translating safety rule system to machine-readable language.

Various kinds of standards may classify unsafe design factors from distinct perceptions and describe the same rule in a changed structure; that is, rules and standards are not organized and standardized for automated rule checking. Therefore, reorganising the rules with a specific format and facilitating rule checking is required (Hongling et al., 2016a). However, all these standards can be classified into safety protection, design computation and design checking. Furthermore, as the rules are used to prevent accidents, the design safety-related information is updated according to accident-related data. Thus, an organised and well-structured safety rule system can be developed (Hongling et al., 2016a).

Several studies developed automated rule checking systems targeting falling (Hongling, Yantao, Weisheng, & Yan, 2016b; Hossain & Ahmed, 2019; Malekitabar, Hassan Ardeshir, Abdollah Sebt, Mohammad Hassan Stouffs, 2016; Zhang, Sijie Sulankivi, Kristiina Kiviniemi, Markku Romo, Ilkka Eastman, Charles M. Teizer, 2015; Zhang et al., 2013b) which are the most common risk to target using automated rule checking. However, many hazards are too complex and interrelated to be automated such as handling equipment and heavy machinery, installations, material control, among others. These kinds of risks are becoming more common to be integrated in automated rule checking (Malekitabar, Hassan Ardeshir, Abdollah Sebt, Mohammad Hassan Stouffs, 2016), but a fully manual approach might be easier to implement while taking advantage of current technologies.



Fully Manual Verification systems

Augmented Reality

"Augmented Reality (AR) is a live view of computer-generated information or image augmenting or laying over the real-world environment" (Vincent, 2012). BIM-based AR advancements within the AECO sector, providing an array of applications. Azuma describes AR as a variation of VR, which provides a natural environment with the incorporation of virtual objects (Azuma, 1997).

Chi and Wang verified that AR technology evolved from marker-based applications towards markerless systems, only uses sensors in the environment to calculate the position and orientation of the camera and does not require prior knowledge of the environment to overlay virtual 3D content into a scene and hold it to a fixed point in space (Chi, Kang, & Wang, 2013). However, recent advances in context-aware tools such as Wikitude, Google's Project Tango, ARCore and ARKit, may expedite the technology used on mobile devices, given the increasing processing capabilities of portable devices (Sidani, Matoseiro Dinis, et al., 2021). Additionally, Data Cloud computing environments have been recognised in server-based applications and a wide variety of applied localisation technologies, dependent on the specifics of the system and the application or task itself. Simultaneously, the potential of gesture-based interfaces and HMDs (Head Mounted Display) were also reported (e.g., applications based on Microsoft HoloLens). BIM authoring tools such as Revit and ArchiCAD and game engines (e.g., Unity) support data transfer and the development of virtual environments (Sidani, Matoseiro Dinis, et al., 2021).

AR is primarily implemented in construction sites due to the visualisation and information extraction capabilities that it can provide. BIM-based AR applied to the construction site to support task completion and reduce construction errors, lower cognitive workload, improve access to project information, manage construction schedules and costs, improve collaboration, increase site assistance, safety training, task orientation, and higher productivity (Bae, Golparvar-Fard, & White, 2013; Jiao, Zhang, Li, Wang, & Yang, 2013; Park, Lee, Kwon, & Wang, 2013; Pour Rahimian, Chavdarova, Oliver, & Chamo, 2019). Specifically, for Architecture and Civil Engineering, AR may reduce construction errors and project design review; improved communication compared to more traditional 2D approaches, time-savings (working hours) and cost reduction, as defined by Agarwal (Charef, Alaka, & Emmitt, 2018). [Figure 1](#) demonstrates a step-by-step framework to develop an effective AR system for the AECO sector. The framework proposes is based on a holistic approach for integrating AR into the construction. Besides, providing AECO actors with an improved understanding of the technology's potential and suitability to overcome some industry barriers. The framework maps the relationship between AR capabilities and potential benefits based on 23 use cases. Furthermore, the relevance of conducting field tests should not be disregarded from AR implementation, as such an approach may ascertain improved user-friendliness and may also contribute to fostering acceptance and long-term usage (Berkemeier, Zobel, Werning, Ickerott, & Thomas, 2019). A compromise must be attained between the development team's know-how, state-of-the-art technology to the extent that possible difficulties in developing the solution can be minimised, and cost and economic aspects.

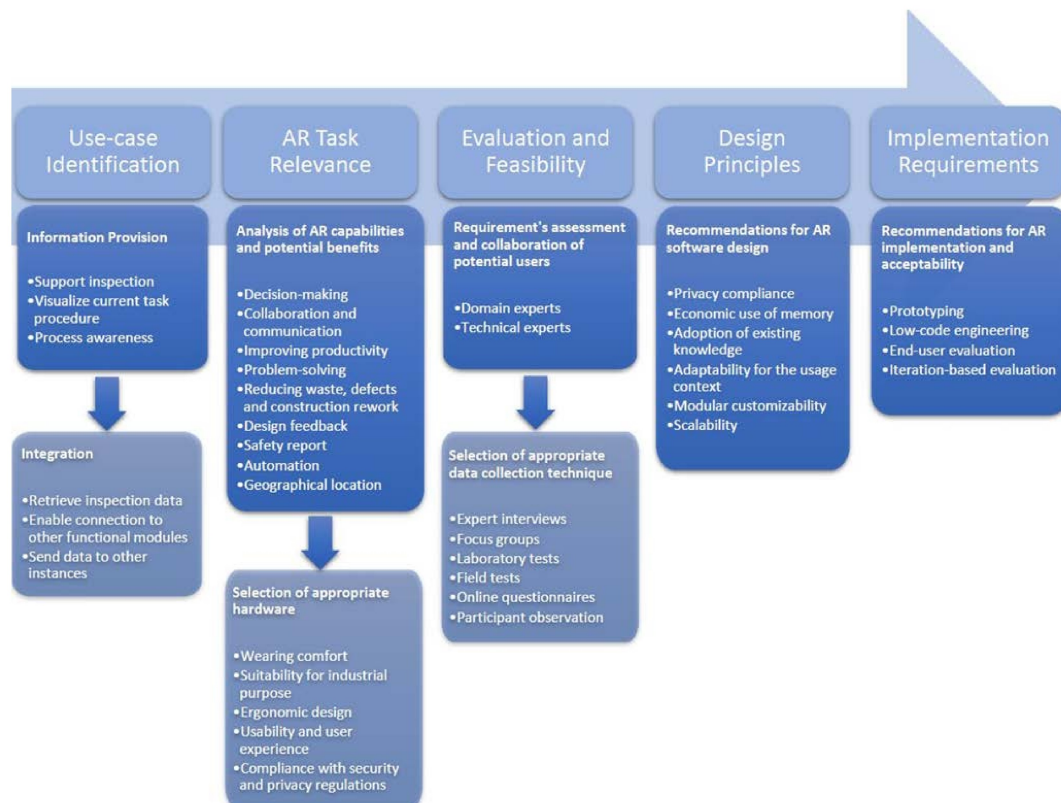


Figure 1 Framework for a Guided Integration of AR in the AECO Sector based on (Berkemeier et al., 2019; Hala, Christian, Makram, & Harald, 2020; Sidani, Matoseiro Dinis, et al., 2021; Steffen, Gaskin, Meservy, Jenkins, & Wolman, 2019)

Virtual Reality

VR has shown encouraging developments as technology prices become accessible to the general consumer and computational power increases (Martín-Gutiérrez, Mora, Añorbe-Díaz, & González-Marrero, 2017). In the last few years, VR research has focused on the AECO sectors, showing potential benefits in a plethora of applications, especially when taking advantage of accuracy and information comprised in BIM models (Li, Wu et al. 2017). Thus, BIM-based VR applications have shown many advantages to enhance design review, team collaboration, decision making, among others. The core idea behind VR application is to enable collaboration and communication, allowing people with different expertise to access BIM information (Sidani, Dinis, et al., 2021).

Kumar and Hare presented an investigation that showed that the site experience is crucial for designers, and it is being reduced in the education curriculums (Hayne, Kumar, & Hare, 2017). Moreover, inexperienced designers do not recognise the impact they can make on on-site safety. Following the author's hazard perception test, an association between identifying and mitigating hazards and possession of site experience was found. The authors recommend that future studies should be undertaken to target educational technologies. VR could offer opportunities to develop solutions that could utilise the parametric attributes and assist with the education and training of designer and new workers (Hayne et al., 2017).

Most BIM-based VR tools utilise a three-layer system architecture comprising a BIM authoring tool, a game engine, and a visual enhancement module. Moreover, some studies expand to a fourth layer, database, to exchange non-geometric information (Sidani, Dinis, et al., 2021). It was also identified that other middleware applications were used to provide network connectivity, creating a multiuser immersive experience; Construction Safety – field focussed on improving the construction site safety, mainly through increased awareness and design simulation (Sidani, Dinis, et al., 2021). [Figure 2](#) illustrates an implementation framework of BIM-based VR.

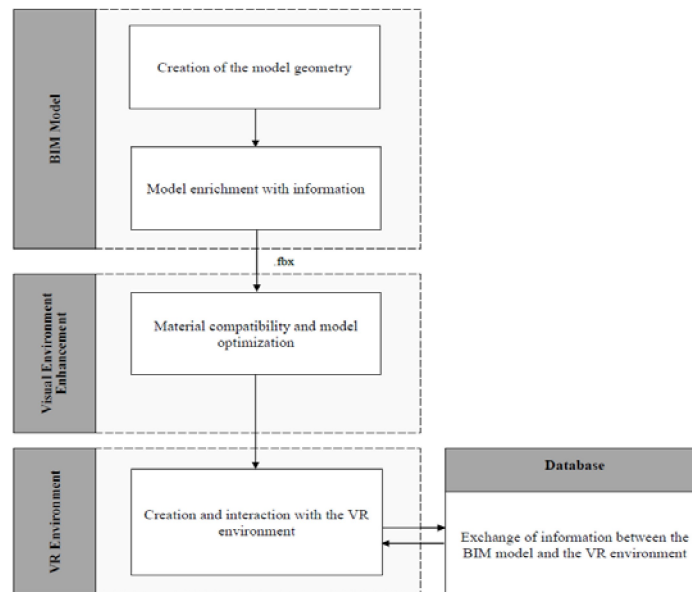


Figure 2 BIM-Based VR Development Framework

Proposed framework

Framework Description

The proposed BIM for Safety framework [Figure 3](#) combines the mentioned technologies generating a BIM for Safety Verification System. This system can be divided into Fully manual or Fully Automated approaches [Figure 4](#). Zhai mentioned that three aspects need to be improved to elevate the levels of health and safety and reduce risks: detecting hazardous areas at a specific time, monitoring and inspection, and training (Zhai, Goodrum, Haas, & Caldas, 2009). the current models are standalone models, either targeting visualization, automated rule checking, or safety management, safety planning but there is no framework combining these methods together and targeting most of the project life cycle and the target group. In addition, this system will be based on European regulations and standards which is mostly missing with the current systems.

Afterwards, the suggested BIM for Safety general framework [Figure 3](#) will be based on the established construction principles, such as EN ISO 19650 1 standard, an international benchmark for operating data over the project's life cycle using BIM. It includes principles and high-level requirements as United Kingdom government's BIM level 2 and is aligned with UK 1192 standards (Panteli et al., 2020).

Furthermore, integrating PAS 1192-6:2018 "Specification for collaborative sharing and use of structured Safety information using BIM". PAS 1192-6:2018 specifies requirements for the cooperative sharing of structured health and safety information throughout the project's life cycles. Supporting the development of structured health and safety data for construction projects gradually from the start. It offers guidance on how safety information is generated, flows, and can be used throughout the project's lifecycle. While all Health and safety risk information can be incorporated within an information model, PAS requires the contextualisation and categorising of hazards and risks to highlight the elevated risks that are critical. It also establishes a risk information cycle framework for the application of safety information through BIM processes and applications. The requirements of PAS can be applied equally to non-BIM projects. PAS identifies how to use Health and safety data to:

- Offer a safer and healthier environment for end-users
- Mitigate hazards and risks across the project's lifecycle
- Improve construction Health and safety performance
- Provide relevant health and safety information to the right people at the right time
- Reduce construction and operational costs

Finally, Directive 92/57/EEC on implementing minimum safety and health requirements at temporary or mobile construction sites will be associated with the framework. The proposed approach for BIM for Safety verification system aims to improve these three aspects by the following:

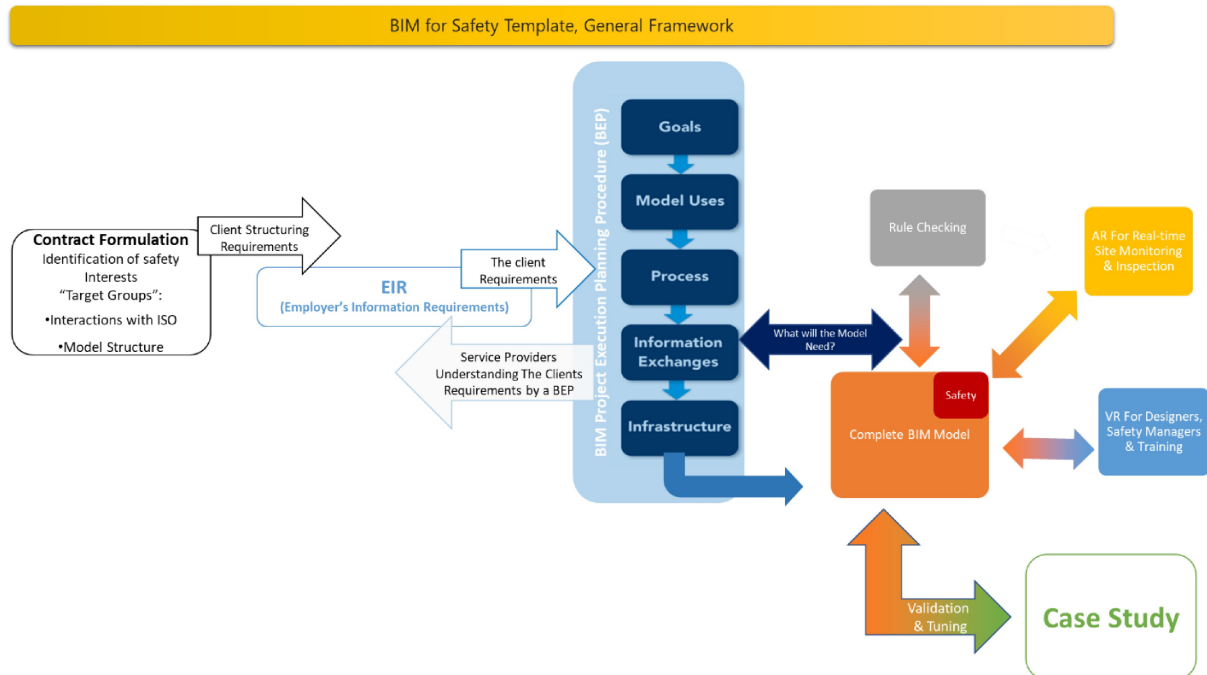


Figure 3 BIM for Safety Framework

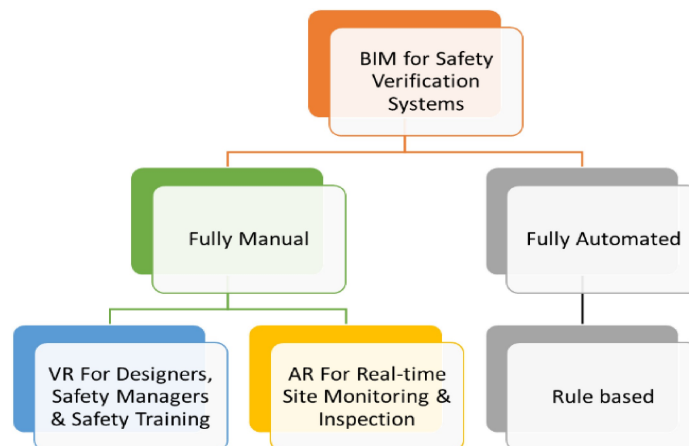


Figure 4 BIM for Safety Verification System

Detecting hazardous areas at a specific time

Since the system is made of a well-identified and structured BIM model, the model then could be introduced to automated rule checking for fully automated risk checking. One of the main problems of construction health and safety is that it is impossible to eliminate all risks due to the dynamic and complex aspect of the construction site. Consequently, several risks scenarios will be identified and analysed at an earlier stage, categorising them based on their Probability, severity, and exposure. Moreover, the rules for each risk will be illustrated. Hence, developing the BIM model with adequate requirements and Level of Development (LOD) facilitates automated rule checking [Figure 5](#).

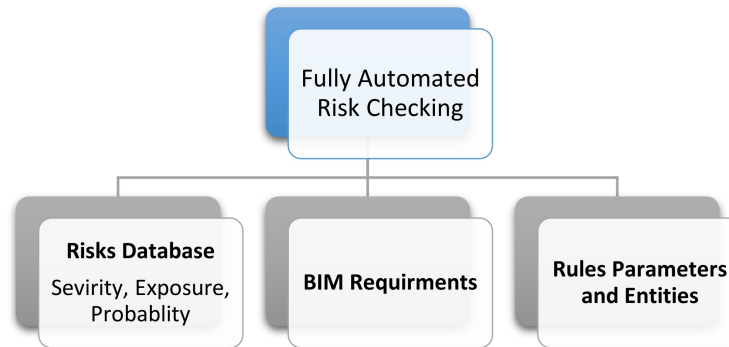


Figure 5 Fully Automated Rule Checking Components

Automated Rule checking aims to cover most of the risks; however, a manual approach will be taken for the risks that cannot be checked automatically. The manual approach is divided into off-site risk checking by using VR and on-site by using AR.

Monitoring and Inspection, and Training

VR will help in identifying risks starting from the design phase up until operation and management. VR can also assist in Health and Safety training. In comparison, AR will be mainly used for on-site inspection, monitoring, and training. To achieve this framework, the BIM model should be prepared with the essential requirements. The data will be transferred to an intermediate converter (e.g., Tridify) to transfer the BIM elements to a readable game engine (e.g., Unity) formats. Finally, the BIM data could be transferred and viewed in a Virtual Environment [Figure 6](#).

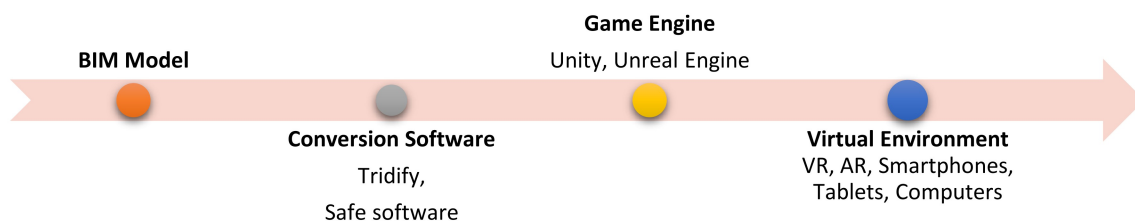


Figure 6 General BIM to Virtual Environment Importation process.

Limitations and Weaknesses

The framework is composed of several digital systems. Each of these systems represents some limitation. The framework's significant limitations are the workers' lack of expertise using digital tools, lack of collaboration between appointed parties, low demand from the owners, incompatibility of data transfer between appointed parties.

The widespread myths about BIM usage and the stubborn mindset of professionals toward validating the facts are delaying the AECO sector from fully integrating the emerged BIM technology. Moreover, the AECO sector is satisfied and is not willing to change the current practices.

As for BIM-based AR, limitations were primarily found in the data transfer due to some construction site's low connectivity levels regarding internet and GPS connections. Nonetheless, there are still constraints regarding non-geometric information being implemented in the AR systems.

Concerning BIM-based VR, software compatibility, the need to create an algorithm to enable the scan of all building objects and parameters, the level of realism of the models, and the implementation of an IFC interface to build a universal data component adopt different BIM packages. The lack of exportation features for the collaboration results. Furthermore, the time spent preparing the BIM model is still a relevant limitation.



Conclusions

The integration of BIM with Automated Rule checking, AR, and VR can indicate the same components of the BIM model by specifying the Level of Information Need, referring to BS EN 19650-1 defines the quality, quantity and granularity of information. Information can be in the form of geometric information (or Level of graphical Detail) and alpha-numeric (or Level of Information).

The proposed framework will be able to target safety planning, Visualization, safety management, training, automated rule checking, monitoring and inspection. The research aims to provide a general framework of a BIM-based safety system to improve the safety status of the overall construction lifecycle.

A Case Study will be made implementing it into an actual industrial project in Portugal. The case study will be presented to provide evidence for the developed system's functionality in coordinating concurrent onsite processes and foreseeing conflicts as well validating the framework with the assistance of safety professionals. The next step will be to elaborate on the proposed safety monitoring and inspection implementation in real practice and presents an illustrative example to showcase the added opportunities. This case also explains how the site planning outputs are interpreted into actual site activities and tasks. Demonstrating how the proposed methodology can assist in the identification of critical timeframes, dangerous onsite zones, and efficient logistics strategies. Finally, implementing the framework's site management component and exemplify a real cases' implementation process.

References

- Abdelhamid, T. S., & Everett, J. G. (2000). Identifying Root Causes of Construction Accidents. *Journal of Construction Engineering and Management*, 126(1), 52–60. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2000\)126:1\(52\)](https://doi.org/10.1061/(ASCE)0733-9364(2000)126:1(52))
- Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modelling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building*, 12(4), 15. <https://doi.org/10.5130/ajceb.v12i4.3032>
- Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6(4), 355–385. <https://doi.org/10.1162/pres.1997.6.4.355>
- Bae, H., Golparvar-Fard, M., & White, J. (2013). High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications. *Visualization in Engineering*, 1(1). <https://doi.org/10.1186/2213-7459-1-3>
- Berkemeier, L., Zobel, B., Werning, S., Ickerott, I., & Thomas, O. (2019). Engineering of Augmented Reality-Based Information Systems: Design and Implementation for Intralogistics Services. *Business and Information Systems Engineering*, 61(1), 67–89. <https://doi.org/10.1007/s12599-019-00575-6>
- BS EN ISO 19650-1. (2018). Organization and digitization of information about buildings and civil engineering works , including building information modelling (BIM) - Information management using building information modelling. *Bs En Iso 19650-1:2018*, 1–46.
- Chan, A. P. C., Scott, D., & Chan, A. P. L. (2004). Factors Affecting the Success of a Construction Project. *Journal of Construction Engineering and Management*, 130(1), 153–155. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2004\)130:1\(153\)](https://doi.org/10.1061/(ASCE)0733-9364(2004)130:1(153))
- Charef, R., Alaka, H., & Emmitt, S. (2018). Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views. *Journal of Building Engineering*, 19, 242–257. <https://doi.org/10.1016/J.JOBE.2018.04.028>
- Chi, H. L., Kang, S. C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction*, 33, 116–122. <https://doi.org/10.1016/j.autcon.2012.12.017>
- Chim, B. L. H., Chun, C. J., & Wah, F. K. (2018). Accidents in Construction Sites: A Study on the Causes and Preventive Approaches to Mitigate Accident Rate. *Inti Jurnal*, 1(3), 1–12.
- Eastman, C., Lee, J. min, Jeong, Y. suk, & Lee, J. kook. (2009). Automatic rule-based checking of building



- designs. *Automation in Construction*, 18(8), 1011–1033. <https://doi.org/10.1016/j.autcon.2009.07.002>
- Eleftheriadis, S., Mumovic, D., & Greening, P. (2017). Life cycle energy efficiency in building structures: A review of current developments and future outlooks based on BIM capabilities. *Renewable and Sustainable Energy Reviews*, 67, 811–825. <https://doi.org/10.1016/j.rser.2016.09.028>
- Enshassi, A., Ayyash, A., & Choudhry, R. M. (2016). BIM for construction safety improvement in Gaza strip: awareness, applications and barriers. *International Journal of Construction Management*, 16(3), 249–265. <https://doi.org/10.1080/15623599.2016.1167367>
- European Commission. COUNCIL REGULATION (EU) No 216/2013 of 7 March 2013. , Official Journal of the European Union § (2014).
- Ganah, A., & John, G. A. (2015). Integrating Building Information Modeling and Health and Safety for Onsite Construction. *Safety and Health at Work*, 6(1), 39–45. <https://doi.org/10.1016/J.SHAW.2014.10.002>
- Hala, N., Christian, S., Makram, B. H., & Harald, U. (2020). A Comprehensive Map for Integrating Augmented Reality During the Construction Phase. *Creative Construction E-Conference 2020*, 56–64. <https://doi.org/10.3311/cc2020-069>
- Hayne, G., Kumar, B., & Hare, B. (2017). Design hazard identification and the link to site experience. *Proceedings of Institution of Civil Engineers: Management, Procurement and Law*, 170(2), 85–94. <https://doi.org/10.1680/jmapl.16.00014>
- Health and Safety Executive. (1999). Reducing error and influencing behaviour. *Structural Survey*, 17(3), 6. <https://doi.org/10.1108/ss.1999.11017cae.007>
- Hongling, G., Yantao, Y., Weisheng, Z., & Yan, L. (2016a). BIM and Safety Rules Based Automated Identification of Unsafe Design Factors in Construction. *Procedia Engineering*, 164, 467–472. <https://doi.org/10.1016/j.proeng.2016.11.646>
- Hongling, G., Yantao, Y., Weisheng, Z., & Yan, L. (2016b). BIM and Safety Rules Based Automated Identification of Unsafe Design Factors in Construction. *Procedia Engineering*, 164, 467–472. <https://doi.org/10.1016/j.proeng.2016.11.646>
- Hossain, M. M., & Ahmed, S. (2019). Developing an automated safety checking system using BIM: a case study in the Bangladeshi construction industry. *International Journal of Construction Management*. <https://doi.org/10.1080/15623599.2019.1686833>
- Jiao, Y., Zhang, S., Li, Y., Wang, Y., & Yang, B. (2013). Towards cloud Augmented Reality for construction application by BIM and SNS integration. *Automation in Construction*, 33, 37–47. Retrieved from <http://10.0.3.248/j.autcon.2012.09.018>
- Kim, J. B., Jeong, W., Clayton, M. J., Haberl, J. S., & Yan, W. (2015). Developing a physical BIM library for building thermal energy simulation. *Automation in Construction*, 50(C), 16–28. <https://doi.org/10.1016/j.autcon.2014.10.011>
- Malekitabar, Hassan Ardeshir, Abdollah Sebt, Mohammad Hassan Stouffs, R. (2016). Construction safety risk drivers: A BIM approach. *Safety Science*, 82, 445–455. <https://doi.org/10.1016/j.ssci.2015.11.002>
- Martín-Gutiérrez, J., Mora, C. E., Añorbe-Díaz, B., & González-Marrero, A. (2017). Virtual technologies trends in education. *Eurasia Journal of Mathematics, Science and Technology Education*, 13(2), 469–486. <https://doi.org/10.12973/eurasia.2017.00626a>
- Mordue, S., & Finch, R. (2019). BIM for Construction Health and Safety. In *BIM for Construction Health and Safety*. <https://doi.org/10.4324/9780429347559>
- Park, C. S., Lee, D. Y., Kwon, O. S., & Wang, X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Automation in Construction*, 33, 61–71. <https://doi.org/10.1016/j.autcon.2012.09.010>
- Pham, H. C., Pedro, A., Le, Q. T., Lee, D. Y., & Park, C. S. (2017, November). Interactive safety education using building anatomy modelling. *Universal Access in the Information Society*, pp. 1–17. <https://doi.org/10.1007/s10209-017-0596-y>
- Pour Rahimian, F., Chavdarova, V., Oliver, S., & Chamo, F. (2019). OpenBIM-Tango integrated virtual



- showroom for offsite manufactured production of self-build housing. *Automation in Construction*, 102, 1–16. <https://doi.org/10.1016/j.autcon.2019.02.009>
- Schwegler, B. (2010). Green BIM: Successful Sustainable Design With Building Information Modeling by Eddy Krygiel and Bradley Nies. *Journal of Industrial Ecology*, 14(5), 859–860. <https://doi.org/10.1111/j.1530-9290.2010.00270.x>
- Sidani, A., Dinis, F. M., Sanhudo, L., Duarte, J., Santos Baptista, J., Poças Martins, J., & Soeiro, A. (2021). Recent Tools and Techniques of BIM-Based Virtual Reality: A Systematic Review. *Archives of Computational Methods in Engineering*, 28(2), 449–462. <https://doi.org/10.1007/s11831-019-09386-0>
- Sidani, A., Matoseiro Dinis, F., Duarte, J., Sanhudo, L., Calvetti, D., Santos Baptista, J., ... Soeiro, A. (2021, April). Recent tools and techniques of BIM-Based Augmented Reality: A systematic review. *Journal of Building Engineering*, Vol. 42, p. 102500. <https://doi.org/10.1016/j.jobbe.2021.102500>
- Steffen, J. H., Gaskin, J. E., Meservy, T. O., Jenkins, J. L., & Wolman, I. (2019). Framework of Affordances for Virtual Reality and Augmented Reality. *Journal of Management Information Systems*, 36(3), 683–729. <https://doi.org/10.1080/07421222.2019.1628877>
- U.S. Department of Labor; Bureau of Labor Statistics. (2019). *NATIONAL CENSUS OF FATAL OCCUPATIONAL INJURIES IN 2019*. Retrieved from www.bls.gov/iif
- Vincent, T. (2012). Classifying handheld Augmented Reality: Three categories linked by spatial mappings. *Workshop on Classifying the AR Presentation Space at ISMAR 2012*. Retrieved from <https://hal.archives-ouvertes.fr/hal-00757883>
- Wang, X., & Chong, H.-Y. (2015). Setting new trends of integrated Building Information Modelling (BIM) for construction industry. *Construction Innovation*, 15(1), 2–6. <https://doi.org/10.1108/CI-10-2014-0049>
- Zhai, D., Goodrum, P. M., Haas, C. T., & Caldas, C. H. (2009). Relationship between Automation and Integration of Construction Information Systems and Labor Productivity. *Journal of Construction Engineering and Management*, 135(8), 746–753. [https://doi.org/10.1061/\(asce\)co.1943-7862.0000024](https://doi.org/10.1061/(asce)co.1943-7862.0000024)
- Zhang, Sijie Sulankivi, Kristiina Kiviniemi, Markku Romo, Ilkka Eastman, Charles M. Teizer, J. (2015). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, 72, 31–45. <https://doi.org/10.1016/j.ssci.2014.08.001>
- Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., & Venugopal, M. (2013a). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, 29, 183–195. <https://doi.org/10.1016/j.autcon.2012.05.006>
- Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M., & Venugopal, M. (2013b). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, 29, 183–195. <https://doi.org/10.1016/j.autcon.2012.05.006>