APPLICATIONS OF IMMERSIVE TECHNOLOGIES FOR OCCUPATIONAL SAFETY AND HEALTH MANAGEMENT IN THE CONSTRUCTION INDUSTRY: A SYSTEMATIC REVIEW

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The construction industry contributes significantly to workplace fatalities and injuries. Recently, Immersive Technologies (ImTs) as part of a suite of industry 4.0 technologies have also emerged as a viable pathway to address poor construction occupational safety and health (OSH) performance. A literature review of 79 articles relevant to the application of ImTs for construction OSH management is conducted to gain a broader view of different construction OSH areas using the preferred reporting items for systematic reviews and meta-analysis (PRISMA) approach. The review revealed that literature has focused on applying various ImTs for OSH areas including safety training of construction workers. This review identified challenges associated with the use of ImTs including the low adoption rate of developed ImTs for construction OSH management. It is therefore recommended that investigations should be conducted to determine the possible reasons for the low adoption rate of developed ImTs for construction OSH management.

Keywords: health and safety; H&S; immersive technologies; systematic review

INTRODUCTION

Schumacher *et al.,* (2016) described industry 4.0 as the modern advancement of technology that utilises the internet and other enabling technologies to integrate physical objects, human beings, intelligent machines, production lines and processes resulting into an intelligent, networked, and agile value chain. Some of the technologies driving industry 4.0 include but are not limited to immersive technologies, big data analytics, additive manufacturing, and internet of things (Salimi, 2018). Immersive technologies (ImTs) can be defined as the 'integration of virtual content with the physical environment in a way that allows the user to engage naturally with the blended reality' (Pavithra *et al.,* 2020, p.1). For example, Truong *et al.,* (2021) observed, in a study on the use of ImTs in addressing the inadequacies of

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2D drawings in construction that ImTs could enhance collaboration and planning bringing significant economic savings and gains for the construction industry.

The construction industry is a very large industry consisting of about 7% of global workforce and contributes about 6% of the world's gross domestic product (GDP) (Adami *et al.,* 2021; Bhagwat *et al.,* 2021). Despite its huge impact on employment and the global economy, the construction industry has an intrinsic dangerous nature making it one of the most hazardous industries (Comu *et al.,* 2021). The International Labour Organisation (ILO) has evaluated that the global annual record of fatal injuries in the construction industry is over 100,000 (International Labour Organisation, 2015). The construction industry is one of the industries with the highest records of work-related accidents and diseases as it has about 3.5 times the average rate of fatal injuries to workers than in all other industries (Health and Safety Executive, 2015). Also, the average rate of non-fatal injuries in the construction industry is about 1.5 times the average rate of non-fatal injuries in all industries (Health and Safety Executive, 2015). The number of fatalities and injuries in the construction industry is very high and requires urgent intervention.

It was also noted that virtual reality (VR), augmented reality (AR) and mixed reality (MR) are the trending realities in ImTs (Pavithra *et al.,* 2020). Wang *et al.,* (2018) refers to VR as a visualisation technique for the creation of virtual environment (VE) with the use of technologies. VR is a technology that utilises computer hardware and software tools to simulate a real environment with a high feeling of presence and immersion in the simulated environment (Raimbaud *et al.,* 2021). These hardware and software tools have been used for the training of construction practitioners in a risk-free and realistic virtual construction site (Zhou *et al.,* 2012). AR, on the other hand, is a technology that complements the real world by generating computerised information such as computer images, videos and texts and superimposing the generated computerised information onto real world layouts (Abbas *et al.,* 2020). In addition, MR as a form of ImT, is "the merging of real and virtual worlds to produce new environments and visualisations where physical and digital objects co-exist and interact in real time" (Dai *et al.,* 2021, p.2).

This study focuses on reviewing the status of application of ImTs as part of a suite of industry 4.0 in addressing the occupational safety and health (OSH) challenges in the construction industry. A few reviews have been conducted on the application of ImTs, especially VR and AR for construction OSH management, but most of these reviews are often individualised owing to their focus on the application of just one or two ImTs on different OSH areas in construction (Li *et al.,* 2018). Other reviews have focused on the use of ImTs for a particular OSH area in construction such as for safety training (Gao *et al.,* 2019). There is, however, the lack of a review that provide a holistic view of the application of ImTs to various OSH areas/topics and different types of OSH hazards in construction. The lack of comprehensive academic documents makes it challenging for researchers and industry professionals to adequately examine as well as ascertain the proficiency of all approaches under all scenarios at a glance. Academic researchers and industry practitioners may therefore not have an in-depth knowledge of the limitations and gaps pertaining to the application of ImTs for addressing OSH challenges in construction due to the overwhelmingly diverse and vast nature of studies in this area (Li *et al.,* 2018). This study aims to coalesce and consolidate understanding of the application of ImTs for construction OSH management by adopting the PRISMA-based systematic literature review (SLR) approach. This implies that there is a very logical approach to the

definition of keywords, database selection, articles inclusion/exclusion and research timeline, which makes it very easy for future researchers to determine the exact contributions as well as limitations of the study. The central research questions this study addresses are:

1. What is the current state of research on the application of ImTs for construction OSH management? What construction OSH areas/topics and hazard types are addressed by ImTs in the academic literature?
2. What are the challenges/limitations and future research directions regarding the application of ImTs for construction OSH management?

METHOD

The Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) approach was used to conduct an extensive systematic literature review (SLR) on the application of VR, AR, and MR for the OSH management in the construction industry. PRISMA methodology has been described as a methodology that consists of detailed items checklist and phase flow diagrams which provides transparent reports during SLRs (Qiao *et al.,* 2021). The literature search was conducted using Scopus (www.scopus.com) which is the one of the largest online, abstract and citation database of scientific literature (Gao *et al.,* 2019). The set of search strings used for the collection of articles from Scopus database is as shown in Figure 1.

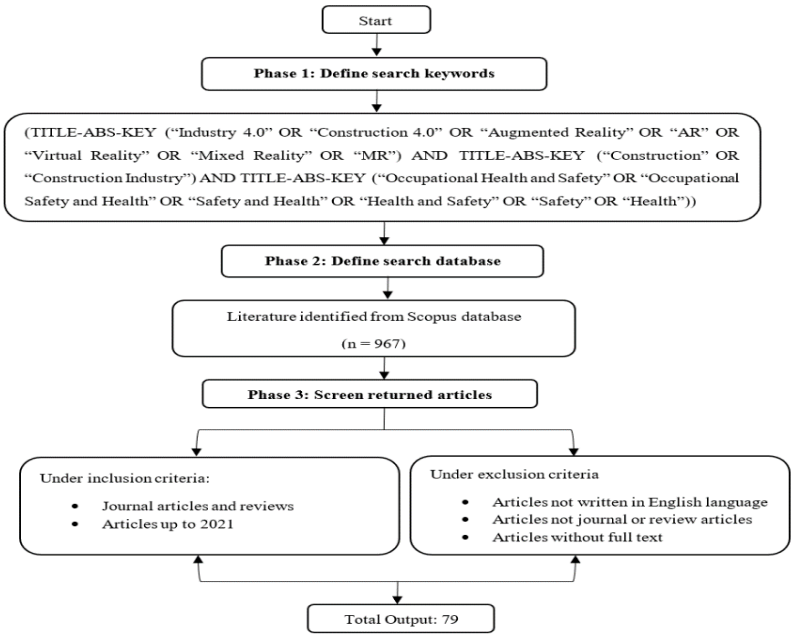


Figure 1: SLR flow diagram

As depicted in the systematic flow diagram shown in Figure 1, the initial search retrieved 967 papers from the Scopus database. The set of search strings was then limited to journal articles and reviews because they tend to provide more comprehensive information on the field of study. The number of journal articles and reviews obtained was 384 with 583 papers filtered out. The titles and abstracts of the papers were then screened and reduced to 87 as 297 papers were not relevant to the scope of study. There were 5 papers without full text leaving 82 papers. The full-text screening revealed 3 irrelevant papers to the scope of study and were therefore excluded resulting in 79 relevant papers, which were analysed for the SLR. The number of papers is sizeable enough to draw valuable insights from the literature as

evidenced by other systematic reviews relating to construction management, including more specifically, the areas of OSH, ImTs and industry 4.0 technologies. Examples are the: 32 articles reviewed in a study about safety leading indicators by Xu *et al.,* (2021) and 41 articles reviewed in a study about VR by Wen and Gheisari (2020).

FINDINGS

The review of the literature clearly shows that several studies have been undertaken in the application of ImTs for the construction OSH management. The annual distribution of the 79 papers is shown in Figure 2 and it indicates an increasing trend in publications relating to the application of ImTs for the construction OSH management from the year 2017 till 2021 as 24 articles were published in 2021 when compared to the 3 articles published in 2017. It can be noticed that there was an undulating trend in the number of publications from 2012 after a 6-year gap and this could be due to the emergence of industry 4.0 concept in 2011 (Yang and Gu, 2021). The subsequent sections examine further the OSH areas/topics and the hazards addressed by the application of ImTs in construction.

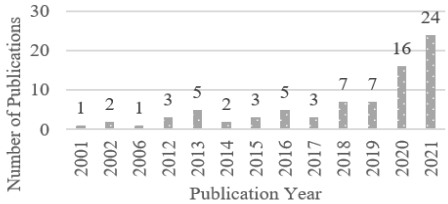
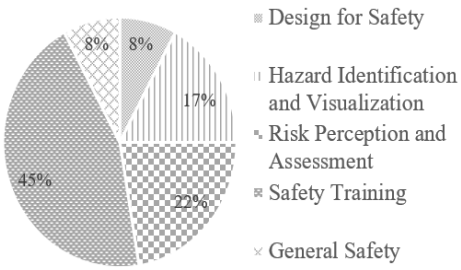


Figure 2: Annual Distribution of Papers

OSH Areas/Topics Addressed by Immersive Technologies

The OSH areas addressed by ImTs as observed in literature are hazard identification and visualisation, safety training, design for safety, risk perception and assessment and general safety. The distribution of these areas/topics across the reviewed articles is shown by Figure 3.

Figure 3: Percentage of publications within construction OSH areas



Hazard Identification and Visualisation

Hazard identification is a key factor in the development of efficient construction-site based management processes (Albert *et al.,* 2014). Kim *et al.,* (2017) proposed a vision-based hazard avoidance system which prevents accidents from occurring by allowing workers to identify hazards through the display of augmented hazard information on a wearable device. However, this AR system which consisted of a vision-based site monitoring module rendered construction site in a planar form thereby limiting the identification of other important hazards by workers (Kim *et al.,* 2017). The planar view of the construction sites has been addressed by Eiris *et al.,* (2018) with the development of an augmented 360-degree panorama of reality

(PARS) that provides a true-to-reality representation of construction sites for effective hazard identification.

Afzal and Shafiq (2021) addressed the planar view of the construction site differently as the issue was addressed with the application of 4-dimensional (4D) building information models (BIM) and VR. VR and 4D-BIM was used in the simulation of construction sites which improved the hazard identification of workers (Afzal and Shafiq, 2021). A similar study conducted by Teizer *et al.,* (2013) presented a 3-D view of primarily steel erection tasks with the application of location tracking sensors and VR for the effective identification of hazardous activities by steel workers. Lucena and Saffaro (2020) conducted a study on the application of VR for the identification and visualisation of hazards.

Participants, who were construction managers, explored the VE and mentioned hazards they identified to the instructors as VR technology provided visual stimuli to participants thereby making it easier to detect dangerous situations intuitively (Lucena and Saffaro, 2020). A similar approach involving the walkthrough of workers in a virtual construction site for hazard identification was adopted in a study conducted by Hadikusumo and Rowlinson (2002). The workers also selected appropriate precautions to the identified hazards for the prevention of accidents (Hadikusumo and Rowlinson, 2002).

Safety Training

The lack of experiential training on OSH is one of the reasons preventable incidents occur in the construction industry and this can be tackled with VR technology for OSH training to minimise incidents at construction site by improving safety awareness of workers (Xu and Zheng, 2021). This is perhaps why 45% of studies on the different construction OSH area focused on addressing construction safety training using ImTs as depicted in Fig. 3. Xu and Zheng (2021) delivered a VR safety training session with the use of VR goggles and a controller which could not enable free navigation of participants in the real world during the training session thereby reducing the realism of the immersive experience.

The effective navigation of trainees was however implemented with the use of a VR treadmill in the virtual dynamic construction site replacing the use of controllers or keyboards (Adami *et al.,* 2021). A study was conducted that compared the conventional safety training method to the VR-based safety training method which involved the collection of eye-tracking data from engineers, construction workers and engineering students (Comu *et al.,* 2021). Alternatively, a similar study conducted by Adami *et al.,* (2021) compared the conventional method of safety training to the VR-based method of safety training for the operation of a demolition robot. While Adami *et al.,* (2021) observed that there was a significant increase in the safety behaviour of workers who participated in the VR training when compared to the conventional training, Comu *et al.,* (2021) realised that different backgrounds of people such as field experience and education contribute immensely to their concentration levels during safety training sessions. Nykänen *et al.,* (2020) extended the study on the comparison of conventional safety training method and the VR-based safety training method by determining the long-term impact of the training methods as a one-month follow up was conducted on participants of the study.

Design for Safety

Designers can play a huge role in the improvement of construction OSH management with VR, a very useful tool, to aid designers make appropriate decisions leading to

safety during the execution of construction works (Sacks *et al.,* 2015). Sacks *et al.,* (2015) therefore conducted pilot tests on designers and construction managers who both have knowledge on safety issues in design and construction as they interact in a virtual construction site and discovered that dialogue makes safety issues in designs more identifiable and clearer, especially for designers. Hadikusumo and Rowlinson (2002) took a different approach in an earlier study as construction practitioners did a walk-through of the VE to identify hazards inherent within the construction components and processes and to determine the necessary and appropriate measures to curb the occurrence of accidents using a design-for-safety-process (DFSP) tool.

Risk Perception and Assessment

Perlman *et al.,* (2014) compared the conventional method and the ImT-based methods through studying to understand how construction superintendents perceive and assess risks on construction sites by presenting subjects with photographs and documents while some other subjects explored the VE. Most of the subjects successfully identified hazards in the VE than the hazards in photographs and documents (Perlman *et al.,* 2014). Lu and Davis (2016) used a different approach by adopting the use of sound to understand how sounds affects the level of risk perception and assessment of construction workers by adding sound to the VR simulator for a set of subjects while the other subjects had no sound included in the VR simulator. It was discovered that participants without the sound experience communicated more to the investigator whenever they perceived risks than participants experiencing sound (Lu and Davis, 2016).

General Safety

Akinlolu *et al.,* (2020) conducted a bibliometric review on industry 4.0 technologies including VR for construction health and safety management and the review revealed that the application of these technologies has greatly improved the health and safety issues in the construction industry. It was also observed that there is an underrepresentation of the application of industry 4.0 in Africa in literature when compared to other continents (Akinlolu *et al.,* 2020). Li *et al.,* (2018) however conducted a critical review focusing mainly on VR and AR in addressing construction safety issues in academic studies. It was discovered that academic studies on VR and AR for construction safety has been conducted from various views which includes safety enhancement mechanisms and technology characteristics with proven efficiency of VR and AR in the general construction safety areas (Li *et al.,* 2018).

Types of OSH Hazards Addressed by Immersive Technologies

As observed in literature, the OSH hazards addressed by ImTs are struck-by hazards (Kim *et al.,* 2021), electrical hazards (Zhao and Lucas, 2015), fall (Bosché *et al.,* 2016) and slips/trips (Afzal and Shafiq, 2021). The various types of hazards could be the reason several studies are looking to improve construction OSH through various initiatives including proposing the use of VR simulation for safety training to mitigate the hazards owing to previously reported effectiveness of VR for construction safety training (Zhao and Lucas, 2015). The leading cause of fatalities and injuries in the construction industry is falling from elevated surface (Habibnezhad *et al.,* 2021). This explains the high number of publications that have focused on fall hazard as depicted in Figure 4. Habibnezhad *et al.,* (2021) therefore proposed a VR simulator in determining the impact of high elevation on gait metrics.

Alternatively, to address fall hazards, Bosché *et al.,* (2016) conducted a study on the use of MR technology to provide trainees exposure on working conditions at height

with positive feedback from the test subjects as they affirmed that the MR system can prepare trainees for working at height conditions that they will later experience in a real construction site. A VR environment that simulates the activities of the construction and maintenance of road construction was created which exposed participants to struck-by hazards (Kim *et al.,* 2021).

The result of the study revealed that 90% of the participants became more cautious of the work environment after being struck by a construction vehicle in the virtual road construction site. A study by Dai *et al.,* (2021) was conducted to understand the potential in MR for the effective visualisation, communication, and collaboration on general construction safety issues as participants who were experienced construction workers in various roles were made to communicate on potential hazards, violations, and suggested preventive measures. Upon the conclusion of the study, it was discovered that MR has a great potential for the effective communication of general construction safety issues amongst workers when compared to communication via phone calls, emails, walking up to people and video conferencing (Dai *et al.,* 2021).

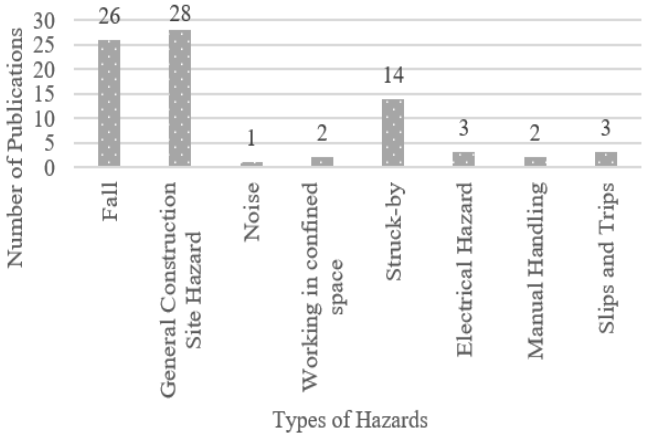


Figure 4: Distribution of publications with the types of hazards addressed

Limitations of Studies and Future Research Directions

The findings from many of the research studies are based on a relatively small number of subjects (Habibnezhad *et al.,* 2021). Some participants of studies experienced headache, eye stress, dizziness and discomfort while using ImTs (Bhagwat *et al.,* 2021). Some studies also researched students rather than industry practitioners (Jeelani *et al.,* 2020) which might therefore not be a true representation of the study outcome. Another limitation observed from the literature is that studies could not expose participants to real-life hazard types such as fall hazards (Eiris *et al.,* 2020) which could affect the study outcome. This is due to the high computational costs and long development times that are involved in simulation an absolute real-life scenario as this would require the geometrical modelling and the assembling of various construction elements in the VE (Eiris *et al.,* 2020). In addition, despite the immense benefits of applying ImTs, the industry has been very slow in adopting these technologies for construction OSH management and this, therefore, needs to be tackled to improve the statistics on construction OSH. Furthermore, as shown in Figure 4, most of the studies have focus on safety-related hazards, with very few exploring the use of ImTs to address health-related hazards.

In view of the discussed limitations, future studies should focus on investigating the transition from research to industry practice. Future studies should also examine the

effectiveness of ImTs for addressing health-related conditions (e.g., musculoskeletal disorders) given their prevalence in the construction industry (Health and Safety Executive, 2015). Aligned to this, further research should also be conducted on how VR, AR and MR can be applied for health hazard identification, risk assessment and control and health training on construction sites. Studies should also be conducted to compare the relative performance and effectiveness of the various ImTs (i.e. VR, AR and MR) for construction OSH management.

CONCLUSIONS

In this study, an extensive review of the application of ImTs for construction OSH management was conducted, which identified the major OSH areas including safety training, risk perception and assessment, hazard identification and visualisation, design for safety and general safety. The review also identified the types of OSH hazards that were addressed using ImTs, including falls from heights, slips and struck-by hazards. Various technologies were used to implement the ImT environment and for the effectiveness of ImTs for construction OSH management. The review revealed immense benefits of applying ImTs for construction OSH management compared to the traditional methods commonly used by the industry. Each year, researchers are ever more interested in the use of ImTs for construction OSH management, especially in the last 6 years, as this study reveals a research increase from 2017 to 2021 with an undulating trend from 2001 till 2016. However, further works need to be done as regards research areas such as investigating the low level of transition from research to industry practice, study of the effectiveness of the use of ImTs for addressing health hazards; and studying the relative performance/effectiveness of the various ImTs (i.e. VR, AR and MR) for construction OSH management. Further works that incorporate bibliometric analysis can be done to augment the insights offered by this study. In addition, other systematic reviews could focus on the broader scope of Industry 4.0 or its sub-domains/concepts such as cyber-physical systems (CPS) and digital twins (DT) to further understand their role in construction OSH management.

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