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Review

Understanding the challenges of immersive technology use in the architecture and construction industry: A systematic review

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A R T I C L E I N F O

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CAVE

A B S T R A C T

Despite the increasing scholarly attention being given to immersive technology applications in the architecture and construction industry, very few studies have explored the key challenges associated with their usage, with no aggregation of findings or knowledge. To bridge this gap and gain a better understanding of the state-of-the-art immersive technology application in the architecture and construction sector, this study reviews and synthesises the existing research evidence through a systematic review. Based on rigorous inclusion and exclusion criteria, 51 eligible articles published between 2010 and 2019 (inclusive) were selected for the final review. Predicted upon a wide range of scholarly journals, this study develops a generic taxonomy consisting of various dimensions. The results revealed nine (9) critical challenges which were further ranked in the following order: Infrastructure; Algorithm Development; Interoperability; General Health and Safety; Virtual Content Modelling; Cost; Skills Availability; Multi-Sensory Limitations; and Ethical Issues.

1. Introduction

Like many other aspects of our life, the Architecture and Construction (A & C) industry is also affected by the implications of the revolution caused by recent advancements in Information and Communication Technology (ICT). Modernisation was one of the biggest challenges faced by the A & C industry. Recently, however, the A & C industry has been exposed constantly to new, innovative tools and technologies, which are capable of improving stagnant productivity. Immersive Technology (ImT) is one such advancement, embraced by the A & C industry. ImT can be described as the use of technology to emulate the physical world in the form of a digital or simulated world in which a sense of immersion is created [24].

Communication with stakeholders in the A & C industry has always been heavily reliant on visual means such as sketches, two dimensional (2D) drawings and images [67]. Further advancements in technology, such as Building Information Modelling (BIM), made it possible to project designs in three-dimensions (3D), which profoundly revolutionised this sector [5]. However, visualisation of such complex 3D information on a 2D interface was still very inefficient and reduced the productivity of this industry [69]. Since it became evident that the complexity of 3D building designs exceeded the ability of construction stakeholders to comprehend [143], the industry embraced ImT as an effective tool that could be applied in multi-dimensional aspects of construction activity such as visualisation, coordination, communication and training [109]. Many studies that are focused on the use of ImT in the A & C industry are now available [50,51,101,144]. It has been identified in these studies that many of the critical problems that arise in the A & C sector are directly related to the inability of site personnel, designers, architects and engineers to experience a project truly before it is executed. In this context, the exciting opportunity for visualisation and interaction offered by ImT captured the attention of the A & C industry [67].

A series of efforts were undertaken during the 1980s to develop ImT, such as virtual reality (VR), and diffuse them into the engineering workflow [156]. However, only recently have improvements in hardware and software rendered the application of ImT viable and worthwhile [91]. According to Berg and Vance [8], the current state of ImT in the A & C industry is “mature, stable and importantly usable”. Gartner’s hype cycle reiterates this and refers the ImT as the “plateau of productivity” [104]. In various studies [80,126,131,157], it has been reported that ImT can be highly beneficial in design, construction and operational activities such as safety assessment, training, space planning, ergonomics and functional requirements, lighting design, interior design,

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evaluation of construction scenarios, facility management and so on. Thus, the application of ImT in the A & C industry belongs to a broad spectrum and the exciting opportunity for immersive visualisation and interaction offered by ImT has captured the attention of a growing number of researchers in the domain of Architecture and Construction. In several studies, various challenges faced by the A & C industry in mainstreaming ImT as an enhanced tool for improving productivity have been reported. However, currently, there has been no research in which these challenges have been integrated systematically and collectively. A systematic review in this area is highly critical, as it will assist in research, decision-making and policies by integrating critical information, as suggested by Mulrow [97]. Thus, the aim of this paper was to fill this gap by consolidating the challenges targeting the A & C industry by conducting a systematic review.

This study aims to fulfil the following objectives:

- To undertake an extensive review of previous studies that focuses on the application of ImT in the A & C industry;
- To present areas of research concentration and paucity in this field;
- To present a synthesis of the evidence available thus far on the challenges associated with the development and use of ImT within the A & C Industry.

The remainder of this paper has been organised as follows: Section 2 contains the background to the enabling technologies of ImT in the context of the A & C industry; Section 3 contains an explanation of the research methods involved in the systematic review; Section 4 consists of the summary and the interpretation of the results; and Section 5 concludes this study by listing out challenges, trends and recommendations for the future research direction.

2. Immersive technology in the A & C industry

Owing to its flexibility in being adapted to different problems and domains, ImT has evolved rapidly in recent years, which has led to different interpretations of a virtual environment [167]. The present state of ImT is built upon ideas that date back to the 1960s [167]. A vast variety of immersive technologies are used to create a virtual environment (VE), with various levels of immersion and capabilities [76,131]. These levels can be divided generally into three, as shown in Fig. 1: a) Passive VE, b) Exploratory VE, and c) Immersive VE [76,131]. Passive VE refers to spectator activities such as watching movies and TV, which might also be referred to as a non-immersive system [96], whereas an exploratory VE involves exploring a 3D environment interactively through a 2D interface, such as a monitor [76] which can be referred to as a semi-immersive system. Immersive VE refers to a synthetic environment where the user can interact fully with the artificial environment with all the senses being stimulated [76]. Therefore, in this study, only those immersive technologies which are capable of providing an immersive VE [32,123], facilitated by a head-mounted device (HMD) or a projection-based display (PBD), are considered.

A variety of immersive VE enabling devices are used in present architecture and construction practice. HMD-based VR is one of the immersive technologies used widely in the A & C sector. HMD-based VR is used to facilitate a truly immersive environment, using a true, stereoscopic, 3D display projected onto both eyes of the users [122,124]. Another type of immersive technology used in the A & C industry is the CAVE system, which has a large, stereo projection system that involves the use of light-weight polarising glasses [67]. Mixed reality (MR), is another type of cutting-edge, immersive visualisation technology, which was recently embraced by the A & C industry [44]. Unlike the HMD-

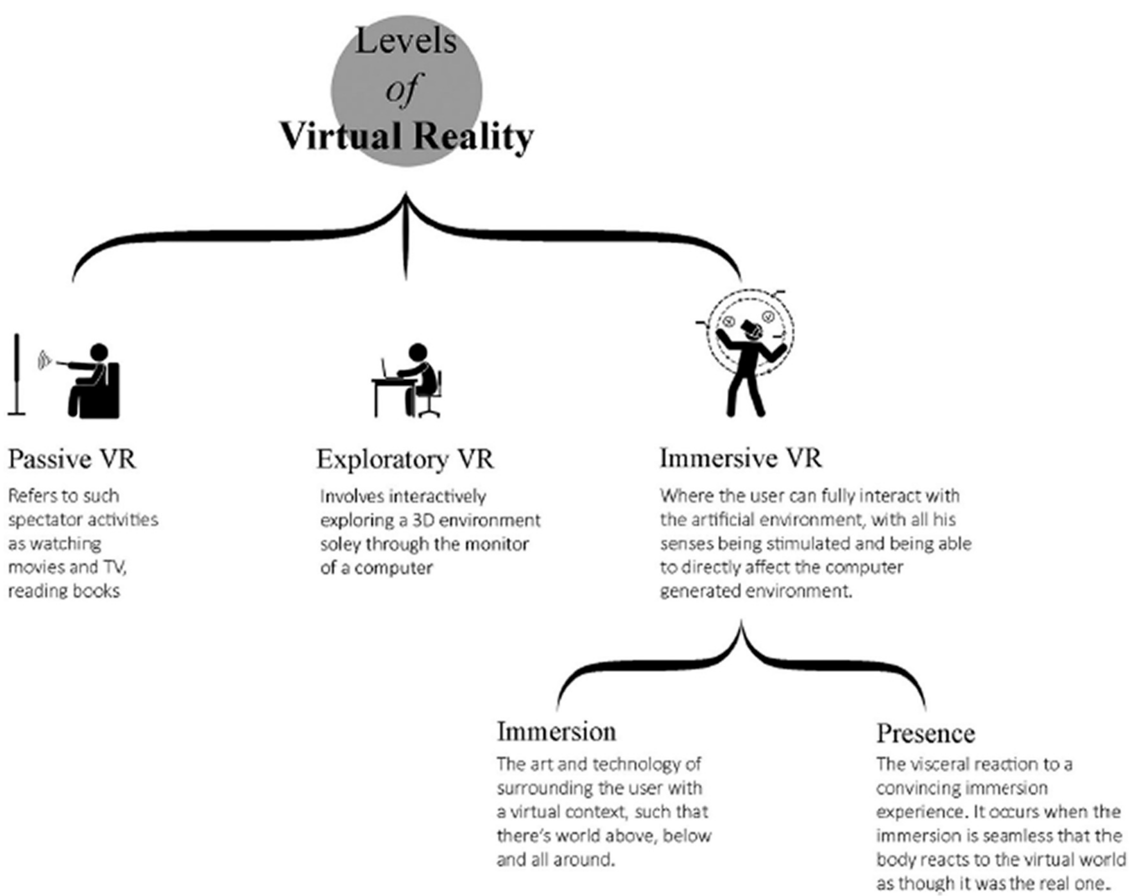

Fig. 1. Levels of virtual reality [131].

based VR, which isolates the user from the real world and secludes the user in a purely synthetic world, MR involves the merging of the real and virtual world [37]. Thus, in an MR environment, computer-generated visual content is superimposed and anchored onto the real world to supplement the user's perception of the real world through an HMD device, such as the Microsoft HoloLens [37]. Therefore, mixed reality is a "reality spectrum" between pure "reality and pure virtual reality" [89].

These Immersive VEs are [108] apable of contributing several benefits, resulting from their application in the A & C industry and, presently, their application [121] omain in the A & C industry is limitless. There are studies [100,46,126] in which it has been suggested that integration of these Immersive VEs during the design phase of a project makes it possible to assess the functionality of space on a true scale by creating space in direct relation to the body, thereby bridging the gap that exists in the present building design process. Similarly, there are studies in which it has been identified that the use of Immersive VEs in architectural practice can dramatically reduce the time and effort required for design tasks through spatial interaction with the 3D models [116,117,149,46]. During the design phase of a project, Immersive VE has been used as an effective tool in building mock-ups to analyse and address issues before the building is constructed [29,40,81]. A one-to-one scale with an excellent sense of realism enables the immersive VE to provide an immersive virtual mock-up, delivering a better understanding of the project to its end-users and stakeholders, resulting in improved and enhanced communication. For this reason, the A & C industry has adopted ImT as a tool for collaborative design [57] to facilitate an excellent avenue for information exchange in a multi-disciplinary environment [62,115]. Furthermore, during the design phase of a facility, researchers have used Immersive VE as a medium to visualise and simulate building user interactions, route mapping within a designed environment [127,128], simulating user energy conception behaviour [39], and simulating crowd behaviour during emergency evacuations [103].

Similarly, ImT has been used to demonstrate effectiveness in construction safety training [1,13,79,113,118,126,154] and other construction-related education [116,117,126,139,151,152]. The capability of ImT to be used to model human behaviour with a high degree of fidelity led Shendarkar et al. [125] to suggest that ImT is an effective tool for conducting emergency management. Similarly, Smith and Ericson [130] revealed that the enthusiasm of users for safety training skills could be enhanced by using Immersive VE to engage with their learning environment. A framework developed by Cheng and Teizer [17] to visualise and simulate construction data for training construction workers is a key study on the application of ImT in the construction phase. Even though there are some gaps in linking ImT and the construction phase of a project, few efforts have been made, such as that of Kamat and Martinez [65], to study the possibility of simulating various construction equipment operations, to identify an optimal solution for construction activity planning.

The possibilities of ImT have been extended to the operational phase of a facility as well, which has quickly attracted the attention of the A & C industry. The real-time data capturing, visualisation and, importantly, interacting with that data are other functionalities contributed by ImT to this sector [47,82]. This has led to the direct use of a virtual environment for planning and daily maintenance of a facility, offering efficient and timely access to information about a building through sensor data and by pinpointing malfunctioning equipment and systems [34,56].

2.1. Commercially available ImT applications for A & C industry

Digital transformation is shaping industries and changing the way humans work across many industries and the A & C supply chain is catching up with the growing popularity of technologies like ImT. Construction supply chain organisations like Caterpillar group, 3 M, Hilti, and ITI VR have already capitalised on the use of ImT to optimise construction-related activities such as earthmoving operations, safety training, work inspection, logistic planning, design communication and risky equipment training simulations for equipment like cranes. Liao et al. [75] suggest that human error or unsafe behaviours contribute to 90% of construction accidents. In this context, the relevance of utilisation of immersive technology for construction-related training by the construction supply chain cannot be overemphasised considering the fact that ImT provides a new opportunity for effective training and education with a higher level of cognition which is impossible to achieve using conventional training methods [74]. Similarly, ImT has been widely used in the A & C industry for risk-prone equipment operations. One of the examples of such a commercially developed VR system is the ITI VR [58] which utilises ImT for overhead crane operator training. Poovladvand et al. [163] reiterates the effectiveness of ImT based system training systems for complex and risky equipment operations such as the use of overhead cranes. Further, the utilisation of aerial surveillance using drones and ImT for construction activities such as site surveying, progress monitoring, work inspection, logistic planning and coordination and hazard identification has also gained momentum [31]. Gray [41] suggest that utilisation of ImT integrated drone surveillance can enhance safety managers efficiency by 50%. Since the seminal work by Schön [164], it has been widely acknowledged that stakeholders and designers occupy an entirely different design world making design communication more challenging. Through the utilisation of ImT, major construction contractors like AECOM (reference), Balfour Beatty, UK (reference) are also reaping the benefits of immersive visualisation and interactivity functionality offered by ImT to communicate its design to the stakeholders effectively, delivering a true sense of the scale and presence. Cumulative evidence suggests that as ImT continues to improve, and its viable commercial use-cases are beginning to emerge. It is worth noting that while there exist a plethora of commercial VR systems, there is a need to explore empirical evidence of the impact and issues associated with their use in practice. One way of achieving this is to thoroughly interrogate published and peer-reviewed publications that have investigated the use of ImT in the A&C context.

2.2. Challenges posed by immersive technology in architecture and construction

There is no denying that ImT possesses huge potential for boosting efficiency in the Construction Sector. Cumulative evidence has indicated the potential of ImT to provide a strong sense of presence [53] that can trigger natural human behaviour, similar to the physical world [50]. As a result of this potential, ImT is considered to be an extremely promising tool for improving the process of architecture and construction workflow [33,84,105,111]. Despite the enthusiasm and hype surrounding the applications of ImT in the A & C industry, there is a substantial gap between the technology that is readily available and the technology that is needed to realise the full potential of ImT systems envisioned in various domains of application in architecture and construction. A substantially improved system is imperative for any technology, such as ImT, to be truly successful and widely adaptable throughout the industry. Therefore, it was imperative to evaluate the current state of the art in the field of architecture and construction systematically to understand the challenges posed by mainstreaming ImT into architecture and construction practice and to suggest how future objectives in this area might be pursued.

3. Research methodology

To achieve the objectives of this study, a systematic review was conducted to explore comprehensively the challenges faced in embracing ImT into the workflow of the A & C industry. Qualitative data analysis was carried out to identify empirical evidence of the challenges posed by ImT. The qualitative systematic review helped to identify findings from various studies on the chosen subject, which helped to accrue a high level of conceptual or theoretical development and achieve a greater understanding beyond what could be achieved through an independent study [12]. The challenge was to analyse the literature in detail, preserving the individual integrity of each study, without being overwhelmed by detail to produce a usable synthesis [119]. The research for this study was divided into the following stages: a) Identification of journals b) Review of journals c) Definition of classification framework d) Classification of journals based on the framework.

3.1. Identification of journals

Inclusion/exclusion criteria were developed to identify suitable literature for review based on the two key questions highlighted by Meline [83]: a) Is the study relevant to the review's purpose? b) Is the study acceptable for review?. Chambers [15] pointed out that reliable inclusion/exclusion criteria are the key elements for a high-quality systematic review, even though a large proportion of the literature (90% or more) might be excluded from the study.

3.2. Inclusion/exclusion criteria

Below are the inclusion/exclusion criteria, based on which suitable literature was identified:

- Articles published between 2010 and 2019 (inclusive) were considered to maintain currency. Since ImT is an emerging development, which is subjected to constant evolutions and refinements, it was imperative to review recent literature to maintain the reliability and currency of the findings, as proposed by Meline [83].
- Only literature referring to Immersive VE was considered to be eligible for this study. As discussed earlier, other forms of virtual environments, such as passive VE and exploratory VE, which do not provide users with full immersion, were not considered to be eligible for this study and were excluded.
- To maintain a predetermined threshold of quality, only rigorously peer-reviewed journals were considered for this study. Conference papers, book chapters or non-international journals were excluded, thus satisfying the best-evidence principle proposed by Slavin [129]. The non-inclusion of gray literature resulting in publication bias might be considered to be a limitation of this study, but the rationale was solely a trade-off between selecting high-quality literature and the inherent risk of broadening the information bias that must be anticipated when a study of doubtful reliability is included.
- Literature in which theory, concepts or proposals are discussed only, without following any experimental testing or case studies were excluded from this study. The development and implementation process of any Immersive VE is a critical element in identifying the challenges faced when diffusing such developments into architecture and construction workflow. Thus, only literature that was focused on development and validation was considered to be eligible for this study.

3.3. Literature identification process

A four-stage approach, shown in Fig. 2, which is built upon the preferred reporting items for systematic literature review and meta-analysis (PRISMA) framework [93] was adopted and the inclusion-exclusion criteria were applied to identify relevant literature for this study. Stage One of the process involved a rigorous search of the relevant databases. It has been suggested in various studies that a minimum of two databases must be considered in a literature search for a systematic review [72,133,134,165].

Two prominent databases (Scopus and Science Direct) within the domain of construction engineering and management were chosen for the literature search. Scopus is one of the largest abstract and citation

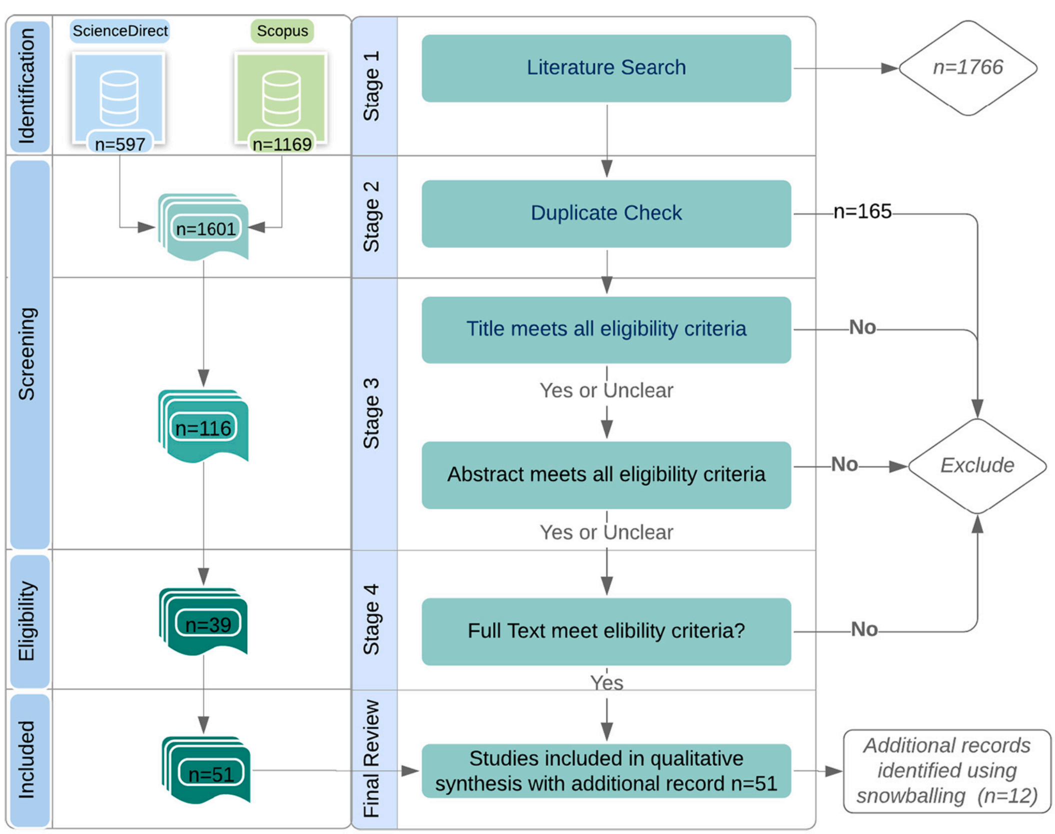

Fig. 2. Literature selection process (author's own).

databases of peer-reviewed literature, with nearly 27 million abstracts, 230 million references and 200 million web pages [6]. Similarly, Science Direct is another world-leading database, covering 12 million publications from 3500 academic journals and 34,000 books, consisting of scientific and medical research [121]. The keywords used to search the literature within the scope of this study were:

> "Immersive Technology" OR "Virtual Reality" OR "Mixed Reality" OR "Augmented Reality" OR "Digital Reality" OR "CAVE Automated System" AND "Construction" OR "AEC" OR "BIM" OR "Built Environment" OR "Architecture".

In the keyword search, augmented reality (AR) was deliberately included. It ought to be noted that, even though AR by its definition is not an ImT [36] and does not meet the inclusion/exclusion criteria, some studies have represented immersive MR as AR [28,150]. Therefore, in the search criteria, AR was added to maintain the inclusiveness, and the literature which did not satisfy the definition of immersive MR [89] was filtered out in Stage Three (title and abstract review) of the study. Thus, a broader keyword search was used, as recommended by Cooper [20], in order not to restrict the amount of literature artificially, but to elicit only those studies that were relevant to the research topic. Similarly, Greenhalgh and Peacock [42] also emphasised the importance of using a broader keyword search for inclusiveness. In addition, backward and forward snowball search methods were also used as a means of retrieving relevant literature. Greenhalgh and Peacock [42] recommended backwards and forward snowball searches as an effective method in identifying literature and maintaining inclusiveness. The search resulted in the retrieval of 1169 literature from Scopus and 597 literature from Science Direct.

Stage Two of the process involved screening for duplication, where duplicate literature (which are common in search results) were removed. This process was carried out at this early stage because the inclusion of duplicates in later stages could lead to double counting of data, resulting in bias as well as leading to unnecessary additional screening efforts. Microsoft Excel's duplicate removal function [87] was used for the duplicate screening process. A total of 165 duplicate files were identified and removed at this stage, resulting in a total of 1601 literature being moved to Stage Three of the process.

In Stage Three, an abstract and title review was performed and only literature that dealt strictly with Immersive VE technologies in the A & C industry were considered. Literature that was inconclusive in the abstract regarding the technology used was cleared for Stage Four (full-text review) and excluded if the criteria were not met. This stage of the process yielded 116 literature that was eligible for the final stage.

In Stage Four, a full-text review was performed, and 39 literature were identified as being eligible for qualitative synthesis for this study. Further snowballing was adopted to identify an additional 12 pieces of literature that were eligible, through a forward and backward search in Google Scholar. The same inclusion and exclusion criteria were applied to the literature identified through snowballing. Finally, 51 literature ($n = 39$ from the database search and $n = 12$ from snowballing) were identified as being eligible for the qualitative synthesis of this study, as shown in Table 1 and Fig. 3.

4. Framework for classifying literature on ImT in the A & C industry

To comprehend and further segregate the eligible literature effectively, a classification framework was developed based on the grounded theory method [38], which consists of the dimensions and categories shown in Table 2. A classification framework for categorising literature about ICT, based on grounded theory, has become an emerging methodology as noted by Urquhart et al. [138]. Therefore, this methodology was found to be suitable for this study.

4.1. Mapping of journal sources

Scientometric analysis was used to identify journal sources that published research based on ImT in the A & C sector.

A total of 26 journals (Table 1) met the threshold when the minimum number of citations and the number of documents were set to 7 and 3 respectively. The nodes of these journals and their inter-relation are shown in Fig. 4, using connecting lines. According to the nodes and the font size shown in Fig. 4, the most influential journals that had been

Table 1
Number of articles by journal and year of publication.

	Total	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Automation in Construction	17					1	1		2	5	8
Computers, Environment and Urban Systems	1						1				
Advanced Engineering Informatics	1									1	
Computers in Human Behaviour	1										1
Journal of Cultural Heritage	1										1
Alexandria Engineering Journal	1										1
Universal Access in the Information Society	1										1
Journal of Information Technology in Construction	2	1								1	
Buildings	1									1	
International Journal of Architectural Computing	2							2			
IEEE Transactions on Visualisation and Computer Graphics	1										1
Lighting Research & Technology	1										1
Computer in Industry	1	1									
Electronic Journal of Information Technology in Construction	1		1								
Computer Application in Engineering Education	1									1	
Multimedia tools and application	1									1	
Construction Management and Economics	1				1						
Architectural Engineering and Design Management	1									1	
Computer Animation and Virtual Worlds	1										1
Sustainable Cities and Society	1										1
Fire and Materials	1							1			
Journal of Computing in Civil Engineering	4						2	1	1		
Journal of Transportation Safety and Security	1							1			
Presence: Teleoperators and Virtual Environments	1									1	
Journal of Construction Engineering and Management	2									1	1
Virtual Reality	1	1									
Visualization in Engineering	3							1	1	1	
Total	51										

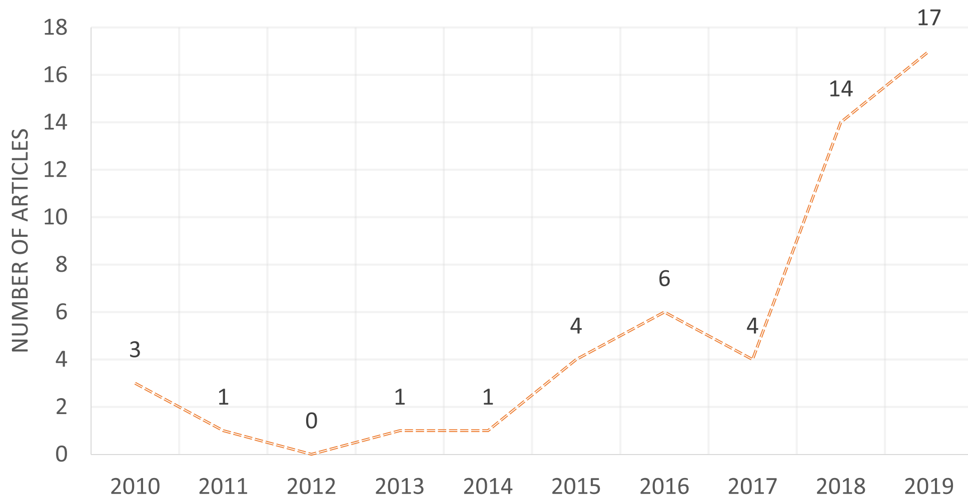

Fig. 3. Yearly publication from 2010 to 2019.
Note: The number of journal papers in 2019 is incomplete, as the articles selected in 2019 was up to the end of September 2019

Table 2
Dimensions and categories of the literature classification framework.

Dimensions	Categories
Improvement Focus	Architecture and Design; BIM; Facility Management; Safety Training; Construction Equipment Training; Construction Education
Research Method	Case Study; Experimental; Proof of Concept; Literature Review; Survey; Interview.
Users	Designers; Contractors; Client/End-user.
Technology Applied	VR; CAVE; MR
Project Phase	Concept Design; Developed Design; Technical Design; Construction; Operation
Maturity of the System	Framework; Prototype; Application Development;
Collaboration and communication in a virtual environment	Multi-User/Networked System
Focus on the sense of Presence	Boolean (Yes/No)
Sense of presence Enhancement focus	Visual; Haptic; Auditory; Olfactory; Interaction
Utilisation Area	Progress Review; Design visualisation/coordination; Defect Detection; Model Validation; Simulation; Virtual Prototyping; Education; Remote communication/collaboration
Challenges	Algorithm Development; Virtual Content Modelling; Interoperability; Infrastructure; Skills Availability; Cost; Ethical Issues; Multi-sensory Limitations; General Health and Safety;

contributing in the research area of ImT application in the A & C industry were: Automation in Construction (AIC), Journal of Computing in Civil Engineering, and Journal of Construction Engineering and Management. The mutual citation among these journals is represented by the connecting lines and the clusters shown in Fig. 4. An inter-relatedness among the journals was revealed through this mutual relation, which meant that the likelihood of one journal disseminating research outputs about the application of ImT in the A & C industry was based on the relevant findings from the other journal.

4.2. Co-occurrence of keywords

Sue and Lee [132] suggested that keywords can be used to provide a clear and concise description of the research content. Furthermore, a network of keywords can be used to depict the knowledge existing between their relationship and the intellectual organisation of the research topic, as noted by Van Eck and Waltman [140]. "Author Keywords" and "Fractional Counting", were used in VOSviewer, as proposed by Hosseini et al. [54], for keyword filtering which yielded 11 keywords that met the threshold. Further, keywords, such as "survey, immersive, office buildings and virtual reality" were removed and keywords that shared the same semantic meanings [136] were identified, resulting in a total of 9 keywords (Fig. 5).

The node size, distance and connecting line between the keywords which are frequently studied (Table 3) are a clear indication of the strong connection between them. Further, each cluster in Fig. 5 is presented in various colours and keywords within the same cluster are closely linked to each other.

4.3. Citation of articles

Articles with a high number of citations were identified using VOSViewer (Fig. 6) by setting the minimum citation number to 10, yielding 6 articles that met the threshold. Table 4 contains a summary of the list of publications with the highest impact in ImT in the A & C industry.

5. Summarising the evidence

5.1. Classification of articles with a focus on improvement

Articles were grouped into five categories based on the improvement that would occur as proposed in the article: (1) Architecture and Design; (2) BIM; (3) Facility Management; (4) Safety Training; (5) Equipment Training. As shown in Fig. 7, 36% of the articles were focused on improving architecture and design practice and the principal focus of 33% of the articles was on improving the BIM process through the integration of ImT. A further 17% of the articles were focused on improving construction safety, and 2% of the articles were focused on equipment training and facility management using ImT.

5.2. Classification of articles based on research methodology

The articles were classified further into three groups (Fig. 7) based on the research methodology adopted in the studies: (1) Case Study; (2) Experimental; (3) Proof-of-Concept. Literature, in which only theory, concepts or proposals were discussed without following any experimental testing or case study, was excluded from this study. The development and implementation process of an immersive environment is a critical element in identifying the challenges faced by such developments for diffusing into architectural and construction workflow. Thus, literatures that were focused on development and validation was

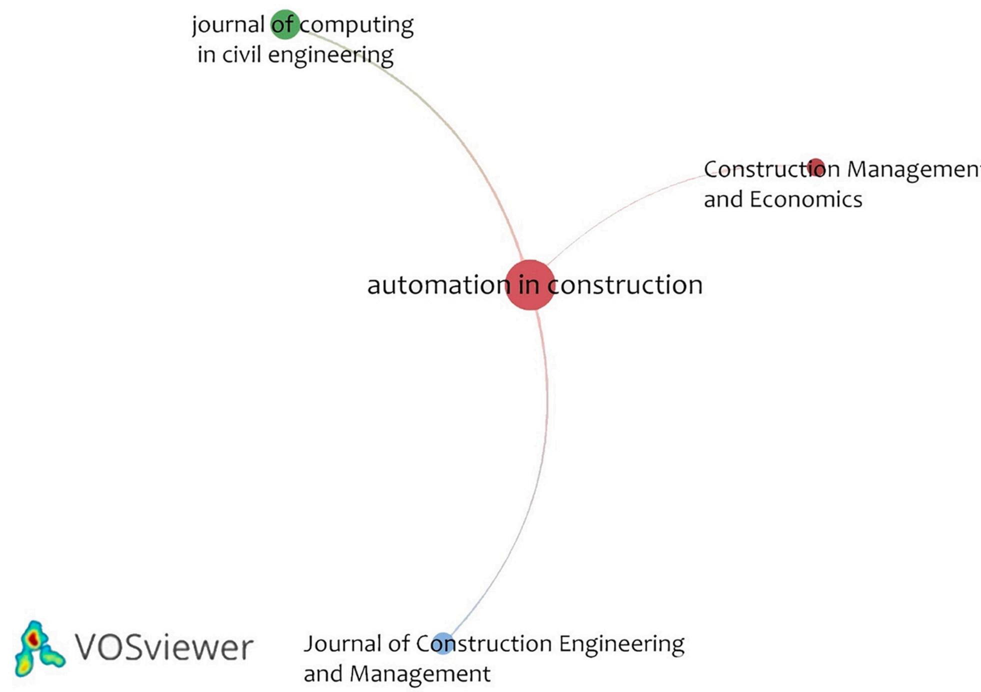

Fig. 4. Mapping mainstream journals in the area of immersive technology in the A & C industry.

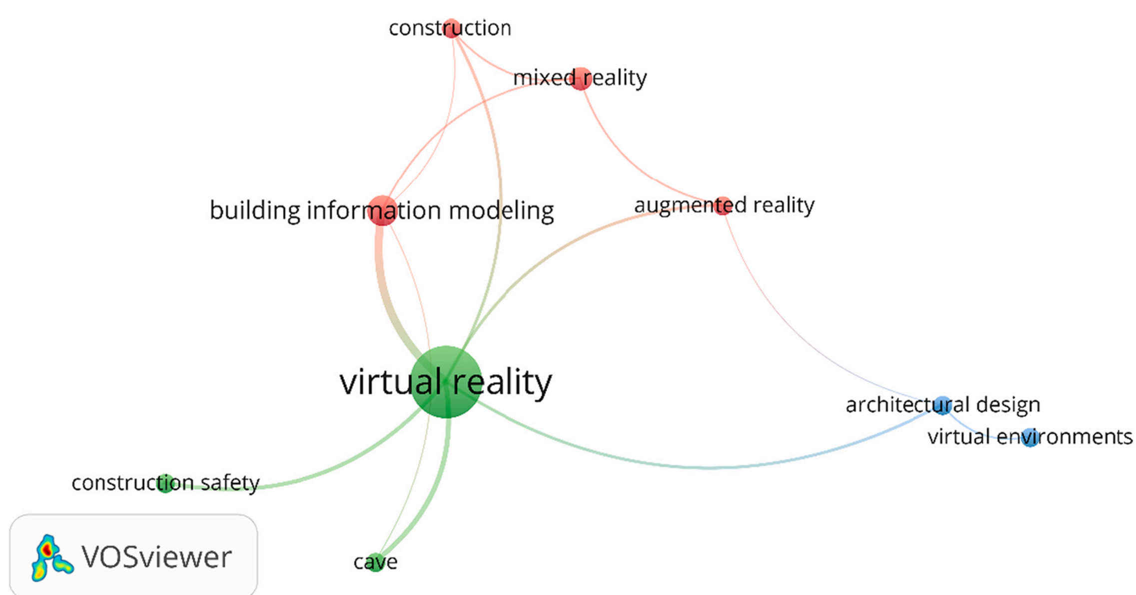

Fig. 5. Network of co-occurring keywords in the research of ImT in the A & C industry.

Table 3
Summary of main keywords in ImT based research in the A & C industry.

Keyword within ImT in A & C	Total Link Strength	Occurrence	Average Year Published	Average Citation	Average Normalized Citation
Virtual Reality	13	24	2017	12.38	1.14
Construction Safety	2	3	2017	27.33	0.33
Building Information Modelling	6	6	2017	13.83	1.16
CAVE	3	3	2014	9.33	1.97
Augmented Reality	3	3	2014	17.67	0.82
Mixed Reality	3	4	2016	8	1.01
Construction	3	3	2016	20	1.13
Architectural Design	3	3	2014	30	1.15
Virtual Environment	1	3	2013	19.67	1.42

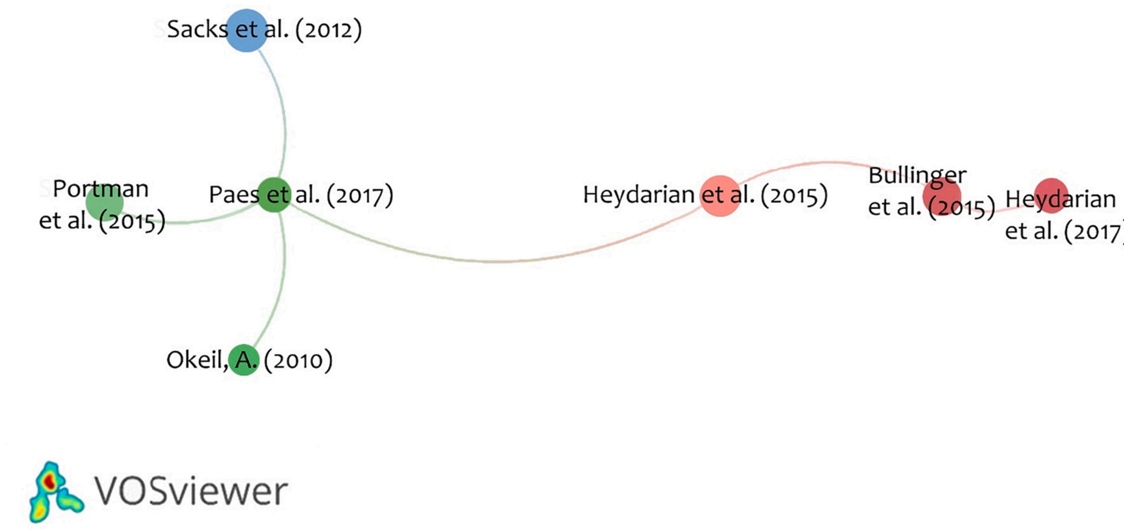

Fig. 6. Network of highest impact publications in ImT based research in the A & C industry.

Table 4
List of publications with the highest impact on ImT based research in the A & C Sector.

Author	Title	Citation	Normalized Citation	Improvement Area	Technology Used
Sacks et al. [116,117]	Construction safety training using immersive virtual reality	82	1	Safety Training	VR
Heydarian et al. [50]	Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations	75	2.31	Arch. & Design	VR
Portman et al. [109]	To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning	47	1.45	Arch. & Design	VR
Bullinger et al. [11]	Towards user-centred design (UCD) in architecture based on immersive virtual environments	43	2.02	Arch. & Design	VR
Paes et al. [102]	Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems	24	1.52	Arch. & Design	VR
Heydarian et al. [51]	Towards user-centred building design: Identifying end-user lighting preferences via immersive virtual environments	19	1.12	Arch. & Design	VR

considered to be eligible for this study. The results showed that an experimental method was used to develop research in 60% of the articles, a case study method was used in 24% of the articles and proof of concept was used in 16%.

5.3. Classification of articles based on the targeted user

Owing to the complexity and collaborative nature of the A & C industry, the beneficiaries of ImT in the construction industry were categorised into three: (1) Designers; (2) Contractors; (3) Clients/End-users. Articles that had a principal focus on enhancing or improving the workflow of any of these audiences were classified under the relevant user category. It ought to be noted that some of the articles targeted more than one user category and they were classified accordingly under multiple categories. The results (Fig. 7) indicated that 37% of the articles targeted designers, 33% targeted contractors and 30% at clients/end-users.

5.4. Classification of articles based on types of immersive technologies

Immersive technology, which typically isolates the user from the real world and is capable of providing a strong sense of presence for the user, makes it harder to differentiate between the real and the virtual world. For this study, only those devices which could provide such an experience for the user were considered. The articles were classified (Fig. 7) based on the type of ImT used for the research. The majority of the articles (67%) used VR, a CAVE automated system was used in 21% of the articles and mixed reality technology was used in 12%.

5.5. Classification of articles based on the project phase

In a construction project, various sequences of steps or project phases constitute the entire life cycle of that project. These stages can be categorised as: (1) Concept Design; (2) Detailed Design; (3) Technical Design; (4) Construction; (5) Operation. ImT was applied mostly in technical design and detailed design (28%), (22%) in construction, (15%) in operation, and (7%) in concept design (Fig. 7).

5.6. Classification of articles based on the maturity of the system

The articles were grouped further into three categories based on the stage of maturity: (1) Framework; (2) Prototype; (3) Application. The results (Fig. 7) showed that the principal focus of the highest number of articles was on developing prototypes, followed by the framework (19%) and fully developed application (7%).

5.7. Classification of articles with a focus on communication and collaboration in the virtual environment

The articles were classified also based on their focus on the use of the distributed virtual environment for remote collaboration and communication. Through the use of the distributed system, geographically

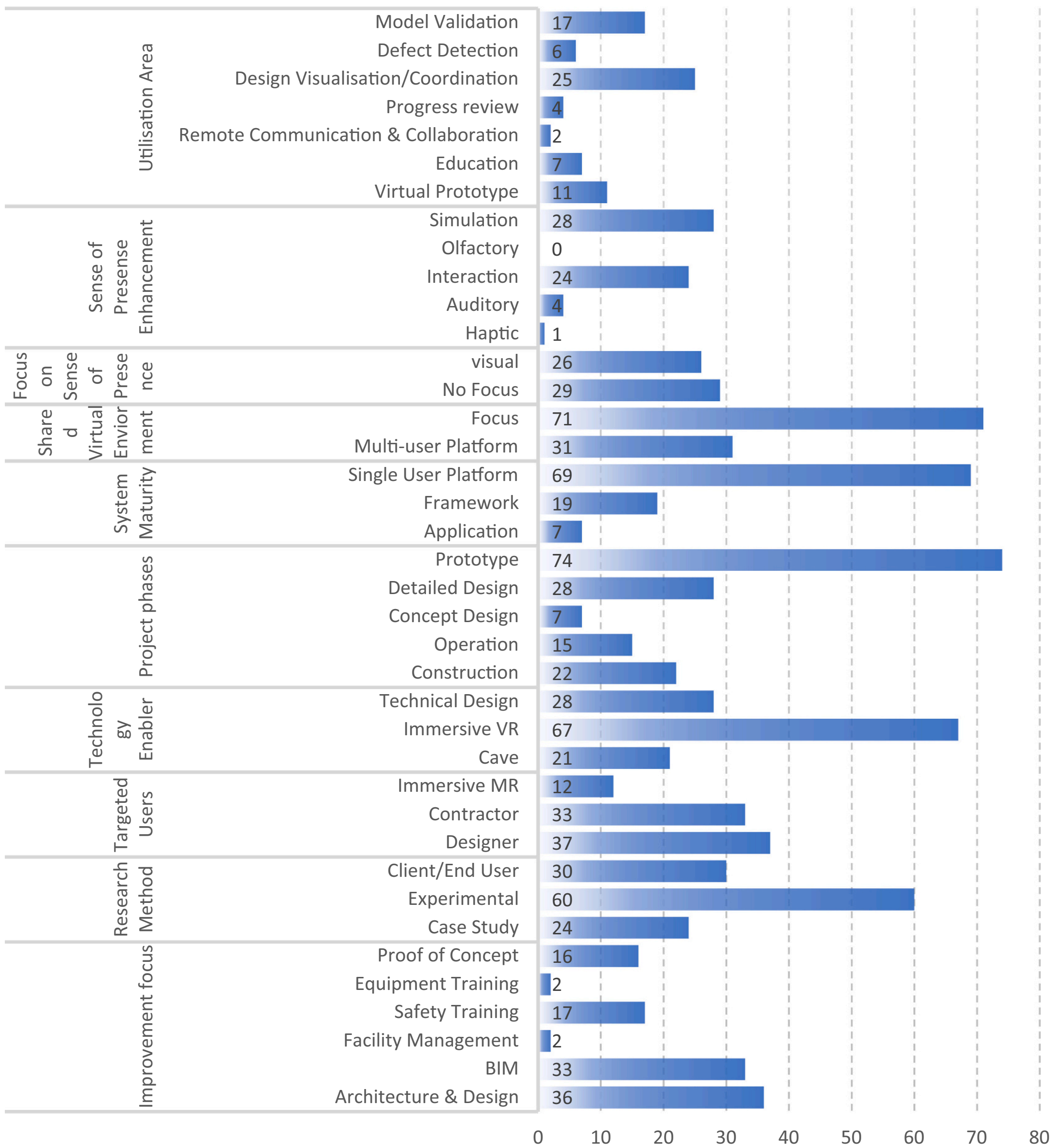

Fig. 7. Number of articles based on the classification framework.

dispersed users are able to connect in a shared virtual space, where interaction between the users and the shared world is possible [45]. Effective communication and collaboration are key elements in the successful completion of any construction activity. This dimension of the framework was used to measure the number of articles in which the research was focused on the use of the distributed virtual environment. Surprisingly, in this category, the focus of a large portion of the articles (69%) was on the integration of a single-user platform (Fig. 7) and the focus of only 31% was on the use of a multi-user virtual environment for communication and collaboration.

5.8. Classification of articles with a focus on the sense of presence

A high sense of presence has proven to be an integral part of an effective virtual environment [78]. The importance of the sense of presence in enhancing the experience and efficiency of task-based activities in the virtual environment has been suggested in various studies [21,78]. Therefore, this dimension of the classification framework was used to categorise the literature based on whether it was focused on enhancing the sense of presence (Fig. 7). Additionally, if there was any focus in the literature on enhancing the sense of presence, another classification (sense of presence enhancement) was used to identify the areas of improvement which was divided into five categories: (1) Visual; (2) Haptic; (3) Auditory; (4) Olfactory; (5) Virtual Interaction (Human-Computer Interaction). These multi-modal cues are critical in supporting performance and improving the user experience and efficiency of the task in the virtual environment [21]. Typically, in an immersive virtual environment, stimulation relies mostly on visual cues [21]. However, factors such as frame rate, visual depth cues, display resolution etc. could have a huge impact on the sense of presence [59]. In this context, it must be noted that the aim of classification based on a visual cue was to identify the literature that was considered for enhancing the visual cues.

Improving various sensory cues was considered in a large percentage of the literature (71%), whereas there was no focus on the sense of presence enhancement in 29% of the literature. In most of the articles (26), enhancing the visual cues was considered, followed by 24 articles that were focused on enhancing natural interaction with the virtual environment and four articles that were focused on enhancing auditory cues. Only one article was focused on enhancing the sense of presence using haptic feedback, and none of the articles was focused on olfactory cues.

5.9. Classification of articles based on utilisation area

The area of application of ImT in the A & C sector belongs to a wide spectrum. In this section, the utilisation area of ImT was classified into eight categories: (1) Progress review; (2) Design Visualisation/Coordination; (3) Defect Detection; (4) Model Validation; (5) Simulation; (6) Virtual Prototype; (7) Education; (8) Remote Communication and Collaboration. The principal focus of most of the literature 28%) was on Simulation (Fig. 7), followed by the use of ImT for visualisation purposes (25%). The focus of 17% of the literature was on the use of ImT for model validation, the focus of 11% was on virtual prototyping, 7% was on education and 6% on defect detection. The principal focus of less than 5% of the literature was on progress review and remote collaboration using ImT.

5.10. Challenges faced by the A & C industry in mainstreaming ImT

While there are several, clear benefits to using ImT in the A & C industry, there are many challenges to the mainstreaming of this technology [84]. In this section, the literature was categorised based on the challenges reported during the research. Nine categories of challenges were identified: (1) Algorithm development; (2) Virtual Content Modelling; (3) Interoperability; (4) Infrastructure; (5) Skills Availability; (6) Cost; (7) Ethical Issues; (8) Multi-Sensory Limitations; and (9) General Health and Safety.

Fig. 8 shows a summary of the challenges identified from 51, eligible, literature. Table 5 shows the theme of each challenge identified, and Table 6 presents the list of articles from which the challenges were identified.

Table 5
Challenges and themes.

Challenges	Definition
Algorithm Development	Challenges associated with programming and the need to develop bespoke scripts that enables interaction and immersion suitable A&C application.
Virtual Content Modelling	Challenges associated with the development of virtual content to be used for immersive visualisation development.
Inter-operability	The capability of the various modelling tools used in the construction industry to exchange data into virtual environment development engines without undergoing multiple iterations.
Infrastructure	Issues that restrain the deployment of the virtual system due to the requirement of a dedicated space, hardware issues such as device weight, view angle, resolution, unrestricted user mobility, frame rate, portability, ease of deployment and device ergonomics.
Skill Availability	The lack of skill among construction professionals to develop and deploy an immersive virtual environment.
Cost	The cost incurred for software development including the purchase of development platforms, training, hardware procurement, the space requirement for deployment.
Ethical Issues	Ethical issues including privacy, security, physiological, behavioural and cognitive impacts.
Multi-sensory requirement	Inability to incorporate multiple sensory modalities other than visual and auditory features to replicate the real-world experience.
General Health and Safety	Safety issues that may lead to accidents and ill-health including colliding with real-world objects, anxiety, eye strain, dizziness, nausea and electromagnetic exposure.

6. Discussion

A full range of articles, published in construction journals between 2010 and 2019 (inclusive), in which the application of immersive technology in the A&C industry was addressed, were reviewed systematically after a thorough search of key databases of research in architecture and construction. Based on rigorous inclusion and exclusion criteria, 51 eligible articles were selected for the final review. Predicated upon a wide range of scholarly journals, a generic taxonomy consisting of various dimensions was developed in this study. The eligible literature was classified and reviewed based on this taxonomy. The findings of the review revealed that architecture and design as well as BIM have been the area with the greatest interest in ImT, being the focus of more than 63% of the literature. This was because immersive visualisation was first embraced in architecture and design, as architects are visually oriented and highly appreciate the requirement for visual cues to communicate their designs [141]. Further, the findings revealed that, when compared with HMD based MR and the CAVE system, HMD based VR was used as the immersive technology in most studies. This was because, even though the concept of mixed reality could be dated back

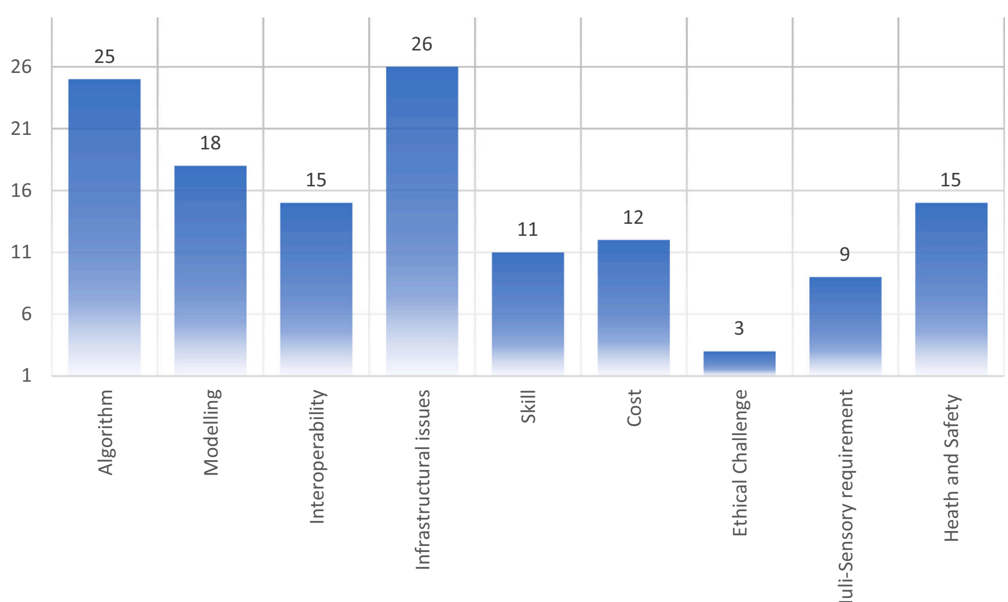

Fig. 8. Classification based on challenges.

Table 6
Literature based on challenges.

Literature	Algorithm development	Virtual Content Modelling	Interoperability	Infrastructure	Skill Availability	Cost	Ethical Issues	Multi-Sensory Limitation	General Health & Safety
Shi et al. [126]	√							√	
Rahimian et al. [110]	√	√	√						√
Portman et al. [109]						√	√	√	
Zhang et al. [157]	√								
Lovreglio et al. [79]	√			√					√
Vahdatikhaki et al. [139]	√								
de Klerk et al. [25])			√						√
Du et al. [27]	√		√						
Heydarian et al. [50]						√			√
Cao et al. [13]		√							
Lee et al. [71]		√		√					√
Chalhoub and Ayer [14]		√		√					
Boton [10]	√	√	√						
El Ammari and Hammad [30]	√			√			√		
Wolfartsberger [149]			√	√					
Bashabsheh et al. [7]		√	√		√				
Wu et al. [151,152]			√	√					
Lucas [80]				√					√
Osello et al. [101]	√	√	√					√	
Miltiadis [92]	√			√					
Liang et al. [73]	√			√				√	
Chen et al. [16]				√					
Okeil [100]	√			√					
Bullinger et al. [11]									
Dunston and Wang [28]	√			√				√	
Wang et al. [144]	√	√	√						
Zaker and Coloma [156]			√	√	√	√			√
Jutraz and Moine [64]		√		√					
Ji et al. [60]	√								
Heydarian et al. [51]	√								
You et al. [154]	√	√							√
Sacks et al. [116,117]	√	√			√				
Gurevich and Sacks [46]	√			√					
Spaeth and Khali [131]		√		√	√	√			
Saeidi et al. [118]	√			√				√	
Ronchi et al. [113]				√		√		√	
Hilfert and König [52]	√		√	√	√	√			√
Natephra et al. [98]			√	√	√	√			
Hou et al. [55]	√	√			√				
Andree et al. [1]		√			√	√			
Zou et al. [159]		√	√						√
Cosma et al. [22]				√			√	√	√
Sacks et al. [116,117]				√		√			√
Bosche et al. [9]				√					
Ren et al. [112]	√	√							
Paes et al. [102]		√							√
Chokwitthaya et al. [18]	√					√			
Wahlstrom et al. [142]		√		√				√	
Hayden et al. [49]				√	√	√			√
Du et al. [26]			√	√	√	√			√
Wu et al. [151,152]	√		√						

to 1994, the first, immersive, mixed-reality concept was actualised only recently, with the introduction of MR, head-mounted devices such as Microsoft Hololens [88]. Owing to limitations in the field of view and rending quality when compared with the head-mounted VR devices [68], MR technology might not be the first choice of architects and researchers for visualisation. On the other hand, a CAVE system can deliver high-quality visualisation, with possibilities of interaction [99]. However, high-cost, complexity of the system and space required to instal a CAVE system might have limited the interest among researchers and the weaknesses in the interactivity of the CAVE system, which is often spatially inaccurate and non-intuitive, have been noted in some studies [48]. Several attempts have been made to develop low-cost systems [85], resulting in poor visual and auditory immersion when compared with the original CAVE concept.

Similarly, the application of VR in construction safety training is a new area of interest for researchers. Training and experience are two key factors that can improve the ability of any construction worker to identify and assess risks [116,117]. However, the inefficiency of current training interventions has been identified in studies [148]. This has prompted academic studies recently to explore the use of innovative intervention methods using VR. Compared with other immersive technology, such as MR and CAVE systems, VR has been proven to be a superior tool for construction safety training because it can seclude the user from the physical world completely, enabling a repeated experience of spatio-temporal events which are sometimes impossible, dangerous and expensive to experience otherwise [107,116,117]. This has possibly influenced the increased reference to VR as an immersive technology in the literature related to construction safety. However, the possibilities of incorporating sensory stimulations other than visual and auditory cues are still an area of research that needs to be addressed [35].

Inefficient communication among critical stakeholders is one of the major issues faced by the A & C industry. The recent development in ImT makes it possible to use shared or distributed virtual spaces, which enables users to communicate, interact and coordinate remotely. However, it was found in this study that most of the research (70%) was focused on single-user systems. The reason might be that the distributed virtual environment was still in its infancy and could cause major latency in information transfer because of network delays which have been noted as a major challenge in research studies [95]. These latencies in information transfer can adversely affect the overall user experience and decision-making capabilities in the virtual environment [27]. However, recent advancements in high-speed internet and the development of cloud-based, independent, network engines such as Photon [108] could alleviate these challenges, leading to many researchers focusing on this area.

The importance of the sense of presence in enhancing the efficiency of the task-based, immersive environment has been noted in various studies [114,158]. It was found in this study that 70% of the literature was focused on enhancing the sense of presence, of which enhancement through visual cues and interaction was the main area of focus. This might be because the emergence of high-end hardware, software and game engines, such as Unity 3D [136] and Unreal Engine [137], has eased the enhancement of visual cues, using a high-definition rendering pipeline (HDPR), and enabled interaction, which was a mammoth task otherwise. However, it was found also in this study that very few or no studies have been focused on the integration of haptics and olfactory functionality in a virtual environment. This was probably because haptic and olfactory technology is still a research challenge, for which many researchers around the world were trying to identify an optimised system to replicate the natural sense of touch and smell.

6.1. Challenges that restrain the mainstreaming of ImT in the A & C sector

The identified challenges were ranked based on the number of reported literature references and the utilisation area, as shown in Table 7 and Fig. 9.

6.1.1. Infrastructure

In this review, it was found that 52% of the literature referred to infrastructural issues, such as device weight, display brightness, view angle, and device portability as the most critical challenges (Table 8 and Fig. 9). Issues related to the weight of the device can have a negative impact on users' acceptance, which will restrain the wider adoption of ImT. In a study by Yan et al. [153], it was suggested that the subjective discomfort of users and pressure load would increase as the weight of HMDs increases. The weight of HMDs has been associated also with the experience of visual discomfort and other injuries [155]. Similarly, it has been noted in various studies that display brightness [2] and view angle [3] have a profound impact on the user's task performance as well as the level of immersion. However, it is noted that, with the advances of the recent chip revolution, HMD manufactures are able to address these issues without compromising the processing capabilities and these

Table 7
Ranking challenges based on utilisation area.

	Progress Review	Design Visualisation/ Coordination	Defect Detection	Model Validation	Simulation	Virtual Prototypes	Education	Remote communication /Collaboration	Mean	Median	Mode	Std-Dev	Mean Ranking
Algorithm Development	3	16	4	10	19	1	1	1	6.87	3.5	1	7.24	2
Virtual Content Modelling	2	10	2	9	10	3	1	0	4.62	2.5	2	4.27	5
Interoperability	4	11	4	8	6	2	3	1	4.87	4	4	3.31	3
Infrastructure	3	18	7	13	16	4	4	1	8.25	5.5	4	6.49	1
Skills Availability	3	9	3	6	5	3	3	0	4.00	3	3	2.67	7
Cost	2	11	2	8	6	3	3	0	4.37	3	2	3.66	6
Ethical Issues	1	1	1	1	1	0	0	1	0.75	1	1	0.46	9
Multi-sensory limitations	0	6	0	5	4	1	0	1	2.12	1	0	2.47	8
Health and Safety	3	10	4	9	5	3	4	0	4.75	4	3	3.28	4
Mean	2.33	10.22	3.00	7.66	8.00	2.22	2.11	0.55					
Median	3	10	3	8	6	3	3	1					
Mode	3	10	4	9	6	3	3	1					
Std-Dev	1.22	4.99	2.06	3.39	5.91	1.30	1.61	0.52					
Mean Ranking	5	1	4	3	2	6	7	8					

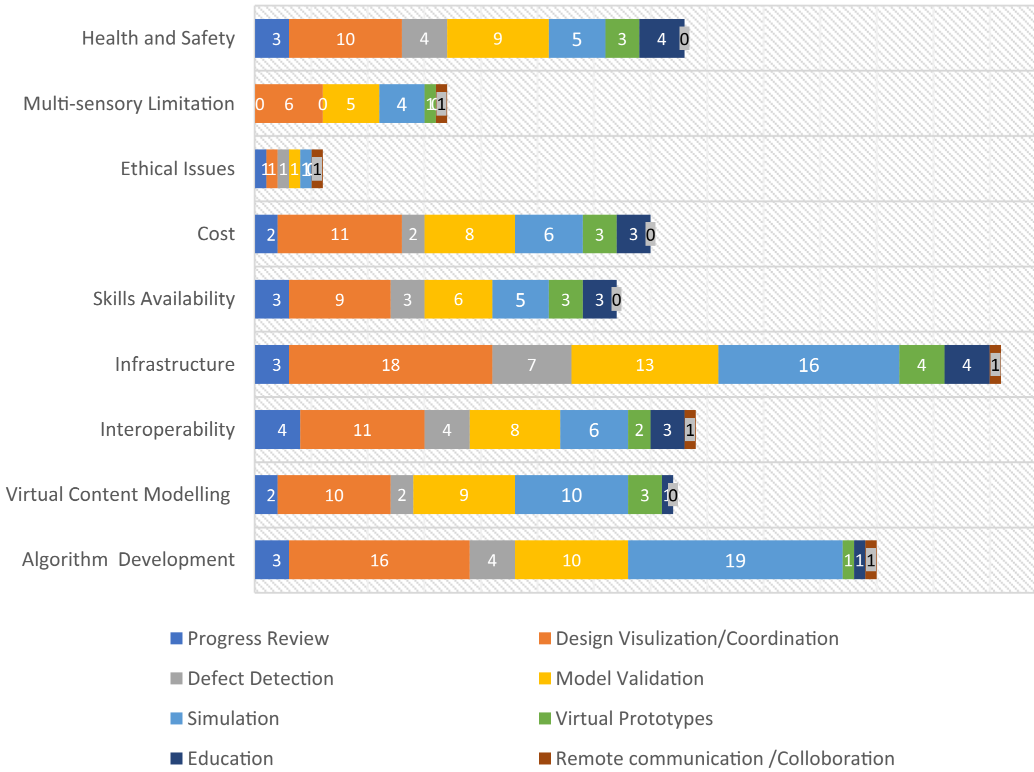

Fig. 9. Thematic analysis of reported challenges.

challenges are expected to be alleviated in coming years [86].

6.1.2. Algorithm development

In more than 50% of the literature, it was reported that developing an algorithm (scripting and programming) that will enable functionalities such as interaction and manipulation in the virtual environment is the second major challenge that could hinder the mass adoption of ImT by the A & C industry. This might be because, unlike in other industries such as the manufacturing and automobile sector, every construction project is unique, and the requirements of the stakeholders are different. Therefore, to enable the virtual environment and the related functionalities to meet the stakeholders' requirements, each project requires tailored algorithms. Moreover, the development of a virtual environment that is interactive, informative, intuitive, immersive and illustrative requires specific development skills, referred to in 22% of the literature as one of the challenges. Any job or trade inevitably changes over time and the required skills sets are also subjected to change. With the A & C industry embracing a faster and more accurate process, there is a clear need for A & C professionals to stay up to date with programming skills. Over the years, there have been constant changes in the way A & C professionals work, and it is evident that this sector is very accepting of new and innovative methods. It is worth noting that architecture and construction curricula should include programming topics as a core subject to keep up with the demand of the jobs as well as the constant changes in technology. With the present shortage of skills throughout this industry [77,120], the A & C sector needs to attract a talented workforce towards the industry. In the absence of this, the A & C industry will have to rely on third-party developers to deliver virtual content that might result in cost overruns.

6.1.3. Interoperability

Media and information-rich virtual environments have proven to be a help, as various construction stakeholders are able to comprehend the design effectively. However, the interoperability between the various construction design tools, such as Autodesk Revit [4], and VE development game engines, such as Unity 3D and Unreal Engine, is a major concern which is necessary to address so that the workflow of architecture and construction is streamlined [110]. Recently, various software vendors, such as Unity [136], have made attempts to bridge this gap using middleware. However, these developments are still in their infancy and require further refinement and iterations using middleware applications. Furthermore, with the introduction of Unity Reflect (Unity [135]), the transfer of BIM models, together with their meta-data, into the Unity game engine to enable an immersive experience has become easier. However, the challenge of creating interaction, which requires tailored algorithms, remains a challenge.

6.1.4. General health and safety

General health and safety issues associated with ImT, such as physical (hygiene, immersion injuries, unnatural postural demands), physiological (visual asthenopia symptoms, convergence cardiovascular changes) and psychological (stress, addiction, change in psychomotor performance), are major concerns while using these technologies [23]. It is critical for any potential ImT user to choose the system based on the tasks and to understand the potential health and safety implications associated with the system. With the advancements in the quality of the display, such as OLED, locomotion techniques used, such as teleportation, light-weight hardware and wireless connectivity between HMDs and computers, it is expected that many of these issues could be mitigated. However, users should take great care to understand the manufacturer's recommended health and safety guidelines. Furthermore, a series of unwanted symptoms, such as nausea and headaches, are often the side effects of the immersive environment [147]. Motion sickness caused by the virtual environment has been related in studies to various factors, such as frame rate drop and latency [146]. However, with the advancements in software and hardware technology, as well as optimisation during virtual content development, these issues can be alleviated to an extent.

6.1.5. Virtual content modelling

To develop VR content that is truly engaging and compelling is a challenge that requires a considerable set of skills as well as resources. For those organisations that have adopted BIM workflow, this challenge might not be as critical as it is for other organisations that are still working towards BIM adoption. As discussed earlier, even though BIM models have to undergo several iterations before being imported into a virtual environment, the mammoth task of modelling the building can be done using BIM authoring tools as a part of BIM deliverables. As mentioned earlier, latest software developments, such as Unity Reflect, enable users to import BIM models directly into the Unity game engine, even though they require post texturing, material enhancing and behaviour assignments, which are time- and resource-consuming tasks.

6.1.6. Cost

In this review, the cost was identified as one of the challenges that could restrain accessibility to ImT devices. This finding was reiterated in a study among construction professionals by Ghobadi and Sepasgozar [166], who concluded that the high cost of peripherals is a major concern for the wide adoption of ImT across various industries. However, unlike CAVE systems which require huge capital investments for installation and maintenance [90], in recent years, HMD manufacturers, such as Oculus etc., are able to bring affordable HMDs into the market [19]. However, it has been shown in studies that this pricing is the "tip of the iceberg" [106] as these headsets require further investments in high-end computers that are capable of rending an experience that is richer and natural, which 52% of participants in a study by Parrish [106] considered to be a major investment that would restrain the mass adoption of this technology. However, at one-tenth of the cost, the current generation of low-cost HMDs is approaching the capabilities offered by large, complex, ImT systems and, in the future, with the advancements in hardware and software technologies, these capability gaps are expected to shrink, further reducing the investments in processors for rendering experiences.

6.1.7. Multi-sensory limitations

Human beings perceive real-world experience through multi-sensory modalities often involving visual, auditory, tactile, olfactory, gustatory and, on some occasions, nociceptive (i.e., painful) stimulations [35]. Most enjoyable experiences of human life involve stimulation of these senses [35]. However, thus far, immersive, virtual experiences have involved the stimulation mostly of visual and auditory senses. However, researchers [35] have proved convincingly that increasing the number of sensory stimulations in the virtual environment can increase users' experience dramatically and, thus, the efficiency of the task. Although haptic and olfactory technology is in its infancy, once mature enough, these technologies will be highly beneficial for tasks that require touch and smell as factors in decision-making [21]. With advancements in technology, it is anticipated that multi-sensory suits (e.g., Teslasuit) will be used to overcome these challenges and introduce affordable technology into the market, which will assist greatly in the A & C industry in activities such as training, product selection etc.

6.1.8. Ethical issues

Ethical issues, such as prolonged exposure to the virtual environment resulting in users facing difficulties in performing normal tasks in the real world, as well as user privacy, were ranked as being the least reported challenge identified in this review. According to Moore's Law, there is a strong correlation between technological advancement and social and ethical impact [94]. While the development of ImT applications is beyond simple entertainment, there has been much debate about the ethical complexities posed by the availability of new, low-cost, ImT devices [61]. It has been noted in studies that these issues include physiological and cognitive factors as well as behavioural and socio-dynamic effects [66]. Kenwright [66] suggested that this challenge could be overcome only through regulations and laws, such as governmental and institutional approvals, and through ethics-in-practice (respect, care, morals and education).

7. Conclusion and recommendation

A systematic review was carried out to understand the challenges faced when mainstreaming ImT into the A & C industry. A structured methodology was used to identify 51 articles, published between the years 2010 and 2019 (inclusive), on the topic of ImT in the A & C industry from two predominant databases, namely: Scopus and Science Direct. Based on this study, it was identified that the most influential journals containing contributions to the research area of ImT applications in the A & C industry were: Automation in Construction (AIC), Journal of Computing in Civil Engineering, and Journal of Construction Engineering and Management. To comprehend and select the eligible literature effectively, a classification framework was applied based on the grounded theory method. In this review, nine categories of challenges were identified that might restrict the mass adoption of ImT in the A & C industry and these challenges were ranked based on the number of references to them reported in the literature.

Potential directions for future research have been identified in this systematic review. It is still necessary to investigate the impact of the various sensory modalities on improving the efficiency of the construction task in the virtual environment. Even though the multi-sensory requirement was considered to be a challenge in only 9 out of 51 literature sources, it is noted that, apart from the usual sensory cues (visual and auditory), very few or no sources were focused on incorporating other multi-modalities such as haptic and olfactory senses. In addition to this, measuring the success of the developed application must be validated by researchers from both academia and industry. The researchers assume that the ImT system will be assessed by the A & C industry, based on the contents, features and value for money. Therefore, any future research should be focused on developing ImT systems that are capable of synchronising project information, preferably in a real-time, user-friendly interface which can be easily diffused into the workflow of architecture and construction and, from a value perspective, can pay back the user in a shorter period. In this literature review, it was found that, in the present state of ImT, most of the system development was at a prototype or trial stage and therefore lacked the above attributes. However, since technology is in a phase of rapid evolution, it is highly recommended that industry partners monitor these developments closely and incorporate those which could bring value.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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