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Review

Integration of BIM and Immersive Technologies for AEC: A Scientometric-SWOT Analysis and Critical Content Review

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Abstract: With the outset of Industrial Revolution 4.0 (IR 4.0), every sector is escalating to get enrichment out of it, whether they are research- or industry-oriented. The Architecture Engineering and Construction (AEC) industry lags a bit in adopting it because of its multi-faceted dependencies and unique nature of work. Despite this, a trend has been seen recently to hone the IR 4.0 multitudes in the AEC industry. The upsurge has been seen in the usage of Immersive Technologies (ImTs) as one of the disruptive techniques. This paper studies the literature based on ImTs, which are Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) integrating with Building Information Modelling (BIM) in the AEC sector. A total number of 444 articles were selected from Scopus following the preferred reporting items for systematic reviews and meta-analysis (PRISMA) protocol of reviewing the literature. Among the selected database, 64 papers are identified as the result of following the protocol, and the articles are divided into eight domains relevant to the AEC industry, namely client/stakeholder, design exploration, design analysis, construction planning, construction monitoring, construction health/safety, facility/management, and education/training. This study adopts both a scientometric analysis for bibliometrics visualization and a critical review using Strength Weakness Opportunity Threat (SWOT) analysis for finding gaps and state of play. The novelty of this paper lies in the analysis techniques used in the literature to provide an insight into the literature, and it provides directions for the future with an emphasis on developing sustainable development goals (SDGs). In addition, research directions for the future growth on the adoption of ImTs are identified and presented based on categorization in immersive devices, graphical/non-graphical data and, responsive/integrative processes. In addition, five subcategories for each direction are listed, citing the limitations and future/needs. This study presents the roadmap for the successful adoption of ImTs for industry practitioners and stakeholders in the AEC industry for various domains. The paper shows that there are studies on ImTs with or without BIM; however, future studies should focus on the usage of ImTs in various sectors such as modular integrated construction (MiC) or emerging needs such as SDGs.

Keywords: building information modelling; immersive technologies; virtual reality; augmented reality; mixed reality; PRISMA; literature review; SWOT analysis; AEC/facility management (FM) industry; sustainable development goals

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1. Introduction

For humans, a vital method of interaction with information is via reliance on communication through the spatial medium. The Architecture Engineering and Construction (AEC) industry is inherently related to the spatial environment and requires the provision of delivering information in multi-dimensional space to uplift the market [1]. With the advancement in computing technologies in the field of construction, we have witnessed myriad changes in the comprehensive approach to designing and constructing buildings.

One such amelioration is Building Information Modelling (BIM) which is defined as a digital illustration of tangible and operative properties of a built asset to facilitate decision making at each stage from inception to demolition [2]. The adoption level of BIM has significantly risen in the last decade around the world to about 73% adoption in the UK industry as per a National Building Specification (NBS) report 2020 [3]. Despite having several advantages, the communication flow in terms of interoperability between various stakeholders limits the adoption and implementation of BIM [4,5], as the walkability in a project on a real scale requires integration with other visualization techniques [6].

The development of Immersive Technologies (ImTs) in recent years provides the solution to this glitch by providing a platform for different stakeholders to get fully immersed during the various stages of the project [7]. ImTs imitate the real world or merge with it through a digital medium to deliver a sense of immersion in the simulated world [8]. Stimulating senses like visual, auditory, tactile, olfaction, and gustation are vital in achieving immersive experiences [9]. Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are the common ImTs that are prominent in the AEC industry for making the user experience more interactive and realistic [6]. Table 1 compares the features of VR/AR/MR in terms of real, virtual, interactive, and immersive levels experienced in each reality. The multiple options provided by integrating ImTs in each project's stage make them a suitable visualization medium for facilitating stakeholders involved at each step [10].

Table 1. Features comparison of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) (adopted from [6]).

Features \ Technique	Virtual Reality	Augmented Reality	Mixed Reality
Virtual/Synthetic content level	High	Low	Medium
Real content level	Low	High	High
Interaction level	Low	Medium	High
Immersive level	High	Medium	Medium

Currently, considerable studies are investigating how to leverage ImTs in the AEC industry. Li et al. [11] highlighted the usage of VR technology for construction workers to identify and assess risks in a construction project through training and experience, finding that VR was an effective strategy that is recommended for construction safety training. In a recent study, Muhammad et al. [12] applied VR for site layout planning and collision detection, showing its effective nature when compared to traditional methods. On the other hand, many BIM-AR investigation models [13–16], research prototypes, and research models also exist [17]. Finally, BIM-MR integration in recent times is quite astounding, ranging from conceptual to operational phases of a project. Naticchia et al. [18] merged information from a BIM model with an MR environment to reflect the maintenance workers' benefits. Another fieldwork facilitated through MR was done by Ammari and Hammad [19], who proposed a framework to collaborate BIM and MR for supporting field tasks in the facility management domain. Most recently, S. Sepasgozar [20] used MR technologies as a digital method for AEC pedagogy in the construction courses for the universities. He presented a combination of five digital technologies using MR techniques and digital twin to add value to the literature by describing the construction courses' effectiveness. Talking about the civil engineering aspects, Protchenko et al. [21] used VR/AR solution to enhance the usefulness of the structural system, and Orihuela et al. [22] proposed the application of the Lean philosophy with the use of immersive applications during the life cycle of a project at different steps. Many universities have increased their research programs focused on ImTs applications in recent years to explore the enormous amount of prominent ways to automate the AEC industry, especially after the outset of Industrial Revolution 4.0 (IR 4.0) [23]. From conceptual and theoretical frameworks to lab evaluated prototypes to field-based knowledge applied results, ImTs has transformed the nature of work in the AEC industry [24] and will continue to do so in the future.

The amalgamation of BIM with these ImTs is not only leveraging the smart and convenient way to be adopted in the AEC industry, rather they have a considerable impact on many other facets, namely the business promotion of projects, research studies in institutions, and enhancing the education of AEC professionals. As a matter of fact, International Data Corporation (IDC) reports the upsurge in ImTs wearables will escalate from 4.2 million numbers in the year 2018 to 53.1 million numbers by the year 2022, which accounts for the significant growth of 88%, also called the compound annual growth rate (CAGR) [25]. Overall, ImTs are providing the solution to the glitch which the construction industry was facing and will be the new dependency tool in Construction 4.0 (C-4.0). Based on the model of IR 4.0, C-4.0 is an amalgamation of construction industry digitalization and construction processes industrialization [26]. Although IR 4.0 is a broad term with no specific definition; its aim is to leapfrog the integration of modern trends and cutting-edge technologies to enhance the way of making things [27]. C-4.0 can be defined as connecting the latest technologies to decentralize the connection of a user to physical space ubiquitously to achieve real-time decision making of a project often called Digital Twin (DT) [28–30]. The development of C-4.0 is still a buzzword, but it will surely gain momentum among researchers and industry professionals, especially after the prevalent COVID-19 pandemic. A recent study by Pavon et al. [31] though utilized BIM possibilities to reduce crowding and facilitate social distancing as a COVID-19 measure in a public building, but in the future more studies will utilize ImTs with BIM to facilitate AEC works.

Although ImTs have great potential to be used for the AEC industry, they are still below par, as ImTs lack robustness [32], especially to be used in tough conditions, usually at construction sites, and thus reliability towards their usage becomes a challenge in the construction sector [33]. The complex and different occurring factors in the AEC sector limit the implementation of digital technologies. Moreover, the construction industry lies very low in adopting new technologies [34]. Although the significance of ImTs is still not completely capitalized on in the AEC industry, it has gain momentum in some other industries already. One such industry is gaming and entertainment, which has provided human consciousness, stimulates human senses, and gives locomotion abilities to players [35]. In the past decade, several literature reviews have been done to show the state of the art of ImTs in the AEC industry. Despite the useful identification of ImTs' research areas, the respective discussions in earlier studies are more focused on the scope of a few domain studies which come under the industry. Additionally, existing review studies have a narrow perspective, focusing on a few domains or on specific applications. As a fact, Zhang et al. [7] reviewed the state of the art of VR applications, giving insights into the benefits and challenges. Cheng et al. [36] reviewed 87 journal papers on MR applications, classifying them into architecture and engineering, construction, operation, and multiple stages. In addition, Diao and Shih [37] reviewed literature from the Scopus search engine to address AR capabilities in the education domain to discover its wide range of advantages and challenges. In fact, a study offering a whole picture of the subject domain in the AEC is still missing. The complex nature of the AEC industry needs an up-to-date, inclusive picture of ImTs through visualizing and understanding trends and patterns to find relevant research themes, keywords, and their link to each other.

As an attempt to fill this considerable gap, this review stands out among the other previous reviews made in this domain to comprehensively present the overall landscape and core perspective of the knowledge body about ImTs in the AEC industry using the Strength Weakness Opportunity Threat (SWOT) analysis method. This study contributes to the sphere of knowledge in the field of ImTs in the AEC industry by identifying the scope and limitations prevailing, assessing the standard of the current and existing body of knowledge. Additionally, presenting cutting-edge technology, highlighting inadvertencies and paucities, and determining the possible future research prospects efforts. The objectives will be to identify and define the current mainstream research topics within this field by finding domains in the industry and SWOT analysis to propose the research directions. Theoretically and practically, the review study will present a valuable point of reference for escalating the knowledge of various stakeholders present in the AEC industry in planning the future agenda concerning the adoption of ImTs in their respective area, along with the implications for both the academics and practitioners to understand as well as find the glitch.

The next section in this study, Section 2, describes the key definitions and concepts, highlighting the overview of ImTs integrated with BIM, summarizing the different definitions and applications related to the AEC industry to understand various terms, perspectives, multiple disciplines, and the theory involved. Section 3 will present the research methodology applied in this study for the systematic literature review. Section 4 analyzes the retrieved papers from Section 3 based on scientometric analysis to reflect the keywords, themes, contributing institutions, and countries in the literature. In Section 5, a SWOT analysis based on content analysis of selected articles is performed along with the limitations of this study. Further, limitations/future needs for the literature are presented in Section 6, finishing with ensuing conclusions in Section 7. A fusion of existing literature and studies in a subject field can elude the recurrence, duplication, and reappearance of like research and studies and will lead to unleashing relevant voids and gaps which are necessary not to be overlooked and unnoticed [38].

2. Key Definitions and Concepts

2.1. An Overview of BIM and ImT's

The knowledge development of a research field is a continuous process, and it is often or most likely motivated through earlier enhancements in it. A joint systematic examination of various knowledge areas will increase the development of BIM amalgamated ImTs by illustrating and knowing the information achieved till now. BIM, as a process, is one such knowledge development in recent years that can store, produce, deal, arrange, substitute, and exchange data from one party to another. The significant part of BIM is it's (I), which is information. Therefore, it can also be summarized by saying Modelling the Information to achieve a Building. BIM uses a methodology to create, share, exchange, and manage the data [39,40]. However, apart from having multiple benefits, its usefulness has not achieved the full credit it should get. Again, the reason for such discrepancy is the flow of information, which is difficult to perceive on a real scale and ultimately reflects the plausible feebleness of BIM. In this regard, the application of ImT's in the AEC industry is a remarkable breakthrough that will stay for a long time as a computing platform for AEC professionals to build innovative ways of learning, connecting with others, and working to eliminate the real world with the virtual world. Li et al. [41] investigated the state-of-the-art application of ImTs in the safety processes in construction. The rapid evolution and advancements in mobile and computer technologies have made it possible for professionals to keep various aspects of their projects in an easy way. ImTs provide the seamless communication of the data, which makes the end-users always and everywhere connected with the virtual environment to get the knowledge of their facility. The synergy of BIM and ImTs paves the way to endless opportunities and possibilities [42]. VR, AR, and MR collectively diminish and blur the opacity between a real and digitally active world with the inclusion of immersion using mobiles, tablets, and other gadgets. This makes the experience more realistic, and will keep on escalating the quality of end products in the AEC industry to a new level.

These immersive realities come under an umbrella name, Extended Reality (XR), which can be termed as a superset, including reality to virtuality as a complete spectrum which is first presented as a concept of reality virtuality continuum [43]. The implication of XR lies through the range of user perspective to senses as VR to cognitive acquisition as AR until complete human-computer communication as MR; the association continues and evolves. Therefore, XR refers to various real-virtual-human computer interactions via Information and Communication Technology (ICT) techniques and wearables techniques. Additionally, X in XR, which is an extended theory, relates to any future spatial recognition within new technologies to come.

Immersion can be summarized into four subsets, namely spatial immersion (virtual effect spatial arrangement), emotional immersion (emotional absorption of a user through content description), cognitive immersion (brain encountering the best result), and sensory motoric immersion (through the recurrence of feedback from senses and actions) [44]. Figure 1 shows the major types of ImTs and immersion levels associated with them. All these technologies have their own share in escalating the AEC sector with VR, which is sometimes called mental teleportation in helping to improve collaboration, facilitate decision making, design communication, better perception, credibility raise of the design, decrease costs, and save time. On the other hand, AR eases design checking, deviation analysis, spatial layout planning, step by step inspection on-site, and logistics. MR also called AR 2.0, makes visualization in 3D reality, facilitates seamless translation, increases helps workflow integration, and improves communication and collaboration among various stakeholders [38]. Following this background, this section will outline the amalgamation of BIM with VR, AR, and MR as ImTs in the AEC industry.

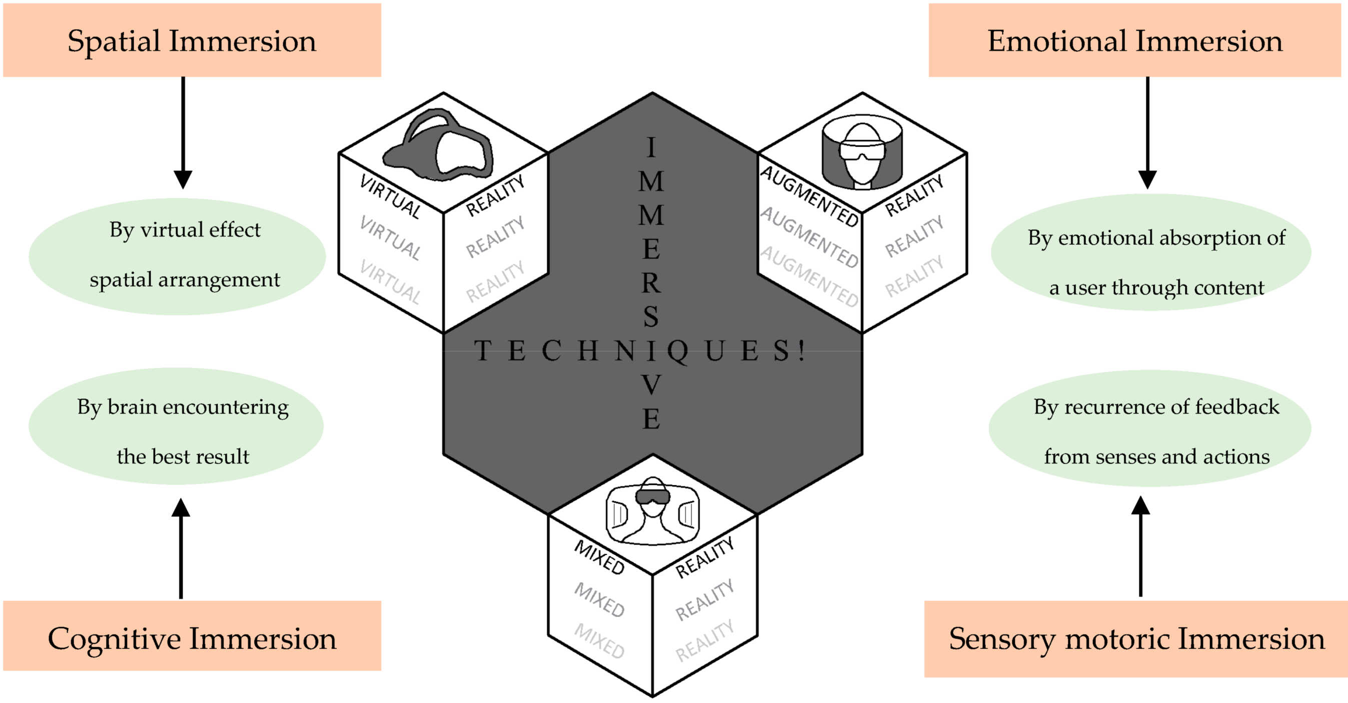


Figure 1. Major types of immersive techniques and immersion levels.

2.2. BIM with VR

The quest of involving clients who have limited or incomplete knowledge of a project is increasing in the AEC industry to give them a better understanding of the outcome [45]. The ability to interact with BIM models can be easily filled by VR, which is a digital mimicry experienced by the user to visualize virtual content by immersing a person in a virtual domain environment to interact with 3D models generated by a computer [46–48]. VR can be achieved by preparing 3D modelling of a project and then generating its virtual reality environment. Most likely used software platforms for 3D modelling stages are Autodesk Revit, Archi CAD, All Plan, Vector Works, Rhinoceros, Sketch-Up, and 3-Ds Max. For preparing virtual environments, software platforms such as Unity 3D, Unreal Engine, and Torque are the most common, among many others [22]. The sense of inclusiveness also makes clients invest more, and they can use this information in their marketing strategies as well [49]. In addition, as construction is a high-risk industry that has a high rate of fatal accidents around the globe, VR can ease the work to estimate the risk and potentially prevent it. The five human senses—vision, hearing, touch, proprioception, and smell can be mimicked by VR through human-computer interactions, and it can also have controlled the generations of signals that six-dimensions (three translational and three rotational) of a human can experience [50].

The literature shows that virtual reality provides a high level of information in an immersive environment, which can be used for training and safety purposes. For example, visualization of underground areas and activities as high-risk spaces for construction can be turned into an immersive environment, and this provides useful information to freshly graduated students and novice practitioners. Figure 2 shows details of a tunnel boring machine, and the user of this immersive environment as an avatar can communicate with other avatars and share their experience and knowledge at the same time. This practice can be applied to other construction activities and can be known as one of the strengths of virtual reality for representing high-risk activities in construction.

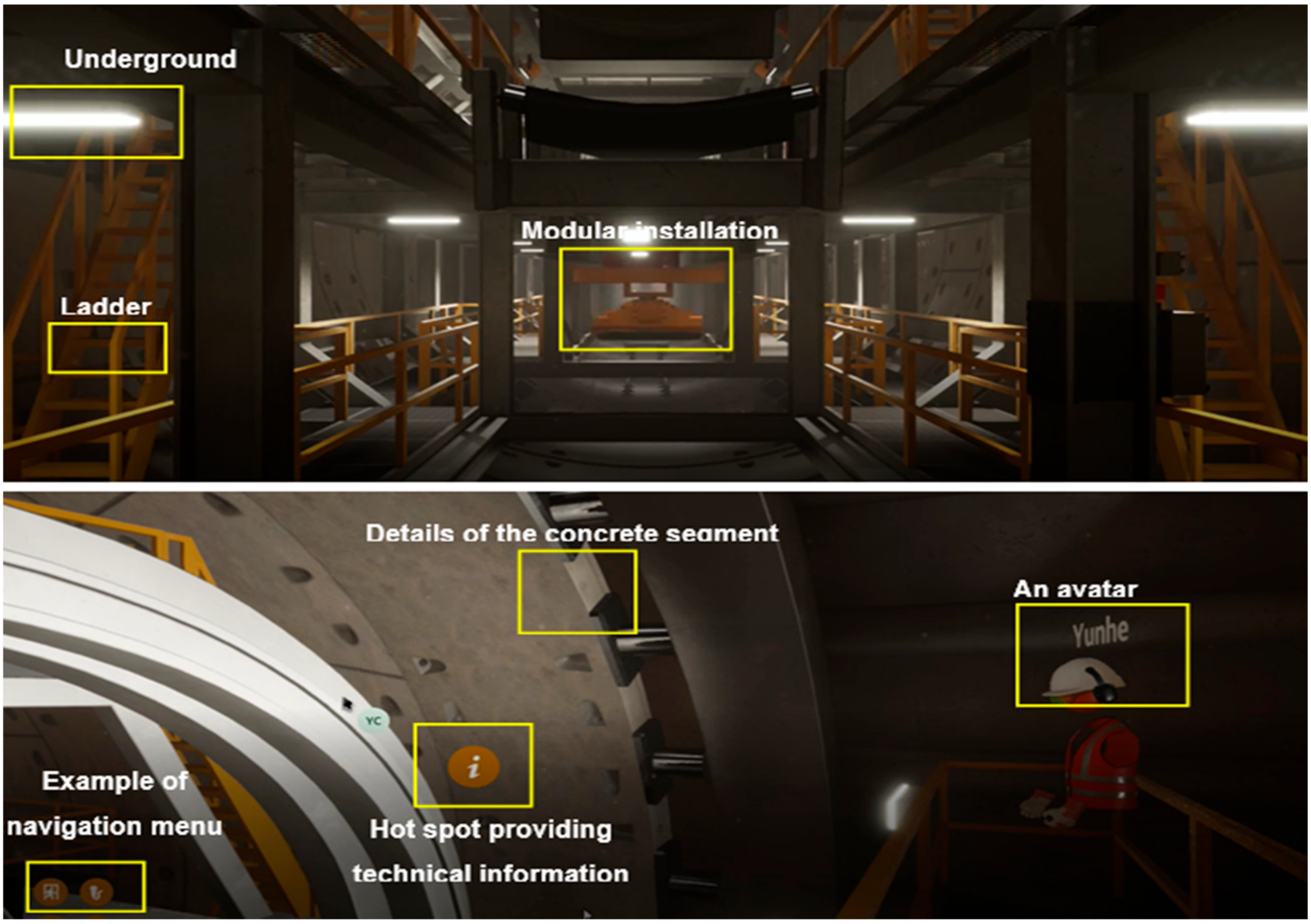


Figure 2. The immersive environment of a tunnel boring machine with the possibility of multi-layer communication as avatars to share their experience of a high-risk operation process in a no-risk environment. (Source: Author).

Along with having a plethora of advantages, the sensitive, cognitive, and perceptual points are sometimes missed in VR [51] due to insufficient sensory feedback, which gave way to AR, and thus MR. The quest for more refined hardware and software used as a technology driver to experience immersive, holistic, tangible, realistic, touchable, and perceptible VR solutions is a search for technology developers around the world to provide a seamless experience to clients [41]. Overall, VR integration with BIM will bring numerous bright advantages in the AEC industry for construction officials, will enhance the collaboration process, and provide a communication platform for real-time interactions [52,53].

2.3. BIM with AR

The vast amount of information that a BIM model holds within it is difficult to structure and exchange, which can affect efficiency at a construction site in addition to a huge amount of time for site workers [54,55]. However, AR is an effective way of retrieving the information and providing a seamless medium to project the information [56,57].

The history of AR is 30 years back when the term is coined by Boeing researcher Tom Caudell in 1990 [58]. However, Azuma's (1997) definition of AR is widely renowned and accepted among researchers, which states AR to be the superimposition of the virtual world over the real world to enhance reality perception [59]. There are many other definitions of AR stating its benefits in the AEC industry by various researchers; some of the definitions are given by [41,60,61] to reflect the added usefulness of the AR environment with BIM. AR is different from VR in augmenting the space with real and virtual information to existing at the same time, where a user can interact intuitively, unlike replacing the real content, which is a drawback of VR [62]. Rather than providing a synthetic reality, AR overlays more information onto reality [63]. AR for AEC dates to the year 1996 [64]. The vast amount of data and interaction involved in the construction project can be accessed easily by AR, thus making it an important and seamless possible way for detecting aspects involved with the view of a user.

Limitations of AR can be technological, user interface centered, and social acceptance by end-users. An AR system is mostly hindered by a lack of effective sensors and trackers with long-range [62]. Although AR is the most effective way to encourage the 3D outputs to date and systems have become advanced in recent years, the sense of nausea, claustrophobia, and motion sickness still occurs on a certain scale, which should be the concern for the researchers and industry persons in the future. The significant drawback of AR is that the user can't interact or manipulate the augmented objects, rather they only add the information. This concern is rectified in the MR environment, which is an extension of AR. Lastly, Microsoft, Google, and Apple are among some tech tycoons who have invested a lot in AR in recent years and propend it to be the next revolution, speculating that the wide reach of AR would be the end of mobile phones.

2.4. BIM with MR

As the name suggests, MR contains the mix of real and virtual world controlling the multiple tasks involved in a facility. MR is a combination of augmented reality (AR) and augmented virtuality (AV) blending to form and produce new visualizations and environments [65]. MR displays the spectrum of reality involving the environment generated through computer-based intervention [66,67], which makes it a potential candidate for the AEC industry, as it requires various levels of relations among stakeholders [68]. VR and AR have a level of obstruction and obstacles, which could not provide an extreme level of interaction; however, BIM-integrated MR being the more flexible environment provides hindrance-free collaboration, which makes it more useful as a marketing tool for developers. The freedom of interacting with the objects and manipulating them simultaneously like in the real world makes MR different from AR and more effective for the AEC industry. The MR systems follow holographic technology, which presents holograms for various digital assets that can be navigated and controlled by gestures, gaze, and voice commands. Although MR and AR are similar in many ways, the application areas of MR are different than AR, as it provides a more realistic, accurate, and immersive form of AR [69]. Table 2 compares some factors to consider when choosing between MR and AR as good, average, and bad.

Table 2. Factors while selecting MR or AR (adopted from [69]).

Considerable Factors	MR	AR
Use of haptics while running the application	Good	Average
Hardware cost	Bad	Good
Ability of spatial tracking	Average	Average
Movement of multiple parts in the application	Good	Average
Large number of objects interacting	Good	Average
High detail level	Good	Bad
Accurate depth representation required	Good	Bad
High immersion level	Good	Bad
Ease of data sharing among other users	Good	Good
Easy hardware procurement	Average	Good
Surrounding awareness	Bad	Good
Object placing on various real surfaces	Good	Average
Devices interaction	Good	Good

Interaction of user with MR, movement of body parts, cognitive and perceptual tasks are some of the ergonomic features which need to be taken care of [70]. On the flip side, the rapid and adaptable growth of MR devices possessing user comfort frequently has the capacity to make the industry compulsive in using them.

As the AEC industry is accident-prone, the incorrect interpretation of information is common, mainly due to a less skilled workforce, which eventually increases the cost of a project, reduces the quality, and delays the schedule. Although the adoption costs of MR techniques are higher ultimately, the firms who will adopt this change will go out to win in the end. Overall, on a rudimentary level, MR will be embraced by the firms in the future at a vast level, as the onset of Construction 4.0 [23,71] will digitalize the industry, providing a paradigm shift in the working culture of AEC firms. The summary of definitions and applications of ImT's is presented in Table 3.

Table 3. Prominent definitions and applications of VR/AR/MR.

	Definitions	Application(s)
BIM with VR	• Combination of 3D models and real time graphics [72] • Illusion experienced by a user between real and synthetics environment [73] • Immersive environment with a combination of multisensory experience and user centred 3D environment [74] • Synthetic environment generated through computer which can be operated as a game by the user for a depiction of real scenarios [75] • Computer driven technique allowing a sense of presence by manipulating user's experience [76] • Obsoletes real world with synthetic objects having sound, videos, graphics and texts in an artificial environment [77] • VR makes immersion and experience of 3D world by making the feeling of 'being there' [78] • A way to escape from the real world temporary [79] • VR enhances immersion, interaction and feeling with the virtual environment [80] • Window towards Virtual World [81]	• Training of site workers [82] • Real time animation [83] • Estimating hazards via dangerous scenarios [84] • Safety training [41] • Schedule control [85] • Optimization of site layout [12] • Collaboration [53,86–88] • Design issues [89] • 3D environment simulation [90] • Project monitoring [24] • Education of AEC students [91] • Decision making in a project [92] • Spatial knowledge and training [93–95] • Enhance the learning of architectural models [96] • Review of the design process [22,97–99] • Client engagement for multiple options [100] • Risk level decrement [101]

Table 3. *Cont.*

BIM with AR	• Superimposition of the virtual world over the real world to enhance the reality belief [102] • Superimposition of information to real world as a textual or graphical way via digital computer-based mediums to provide, enhance & increase its experience [103] • Augmenting the space with real and virtual information to exist at the same time where a user can interact intuitively [62] • Intersection of real and virtual content generated through computer to interact the environment in a superficial way [41]. • Integrating data from real world and computer-generated medium to enhance the user's environment [51,104]. • The technological enhancement of reality by the use of digital medium such as smartphone, tablet and head-mounted display [105] • Acquiring of information by imposing real and digital world data to generate a mixed informative world through wearables like desktop applications, standalone devices and mobile devices [61]. • AR augments the user's real-world scenario's in the form of textual and graphical information, thus enhancing the normal experience to digital avenue [106–108]. • AR enables the viewing of real world and virtual world information together by superimposing virtual over real, predominating the real world scene [109–111].	• Architecture design [10,60] • Construction management [107,112,113] • Safety and health of site workers [114,115] • Project scheduling, cost reduction and cost-effective solutions [116–120] • Decrease man labour hours for a project [104,119–121] • Better communication and information retrieval [122–124] • Apprehending construction of building pipes [125] • Improves the processing of data and progress communication at site [110,117,119,126] • Improves conventional methods of project visualisation, monitoring and control of activities [60,127] • Reduces construction time, cost and effort [125] • Better information modelling and information access [128] • Potential benefits in layout, excavation, positioning, inspection, coordination, supervision, commenting and strategizing [109]
BIM with MR	• MR is a combination of augmented reality (AR), and augmented virtuality (AV) blending to form and produce new visualisations and environments [65]. • MR combines both real and virtual environments blurring the lines between the two and displays the spectrum of reality involving the environment generated through computer-based intervention [66]. • MR is an extension to AR, which delivers interaction between real and virtual elements in an environment [36]. • MR changes the information of a BIM model and can feed the regenerated visuals back to the model [129] • Sometimes termed as Hybrid Reality, MR combines the features of VR and AR in the best possible way by making the interactions of the user more realistic, mimicking it's perspective and behaviour with the elements in the scene [130]. • MR combines real and virtual worlds to generate novel situations, environments and visualisations, creating a co-existence of physical and digital objects [131]. • MR creates a 3D developed space combining auditory, visual, spatial, and haptic cues to diminish the gap between the real and synthetic world [132–134]. • The anchoring of real and virtual world to provide a hybrid reality where information from both the world can interact in real time [6,135–137]	• Construction management [18,136–141]. • Design review collaboration [142]. • Design review performance evaluation and design analysis and optimisation [51]. • Daylight analysis [143]. • Ventilation strategy, structure analysis [144,145]. • Design training and sustainability analysis using game technique [146]. • Site monitoring and inspection of site defect [120]. • Design visualisations [51,68,147]. • Interoperability among stakeholders like information retrieval, information updating and sharing [108,124,148,149]. • Safety and risk assessment [120,150,151]. • Facilitating construction tasks [70,152]. • Construction worker training [153,154]. • Construction equipment operators training [155–157]. • Detection and assessment of defects during the operation phase of a project [158–160]. • Stakeholder's involved [61,104,105].

3. Research Methodology

3.1. Articles Retrieval

To organize the literature for the review process, the PRISMA method is used [161]. It is a systematic collection method of data following the four-step process of identification, screening, eligibility, and inclusion of the records. Similar studies have adopted this approach for the review process and content analysis [162,163]. Figure 3 explains the collection process through the PRISMA approach.

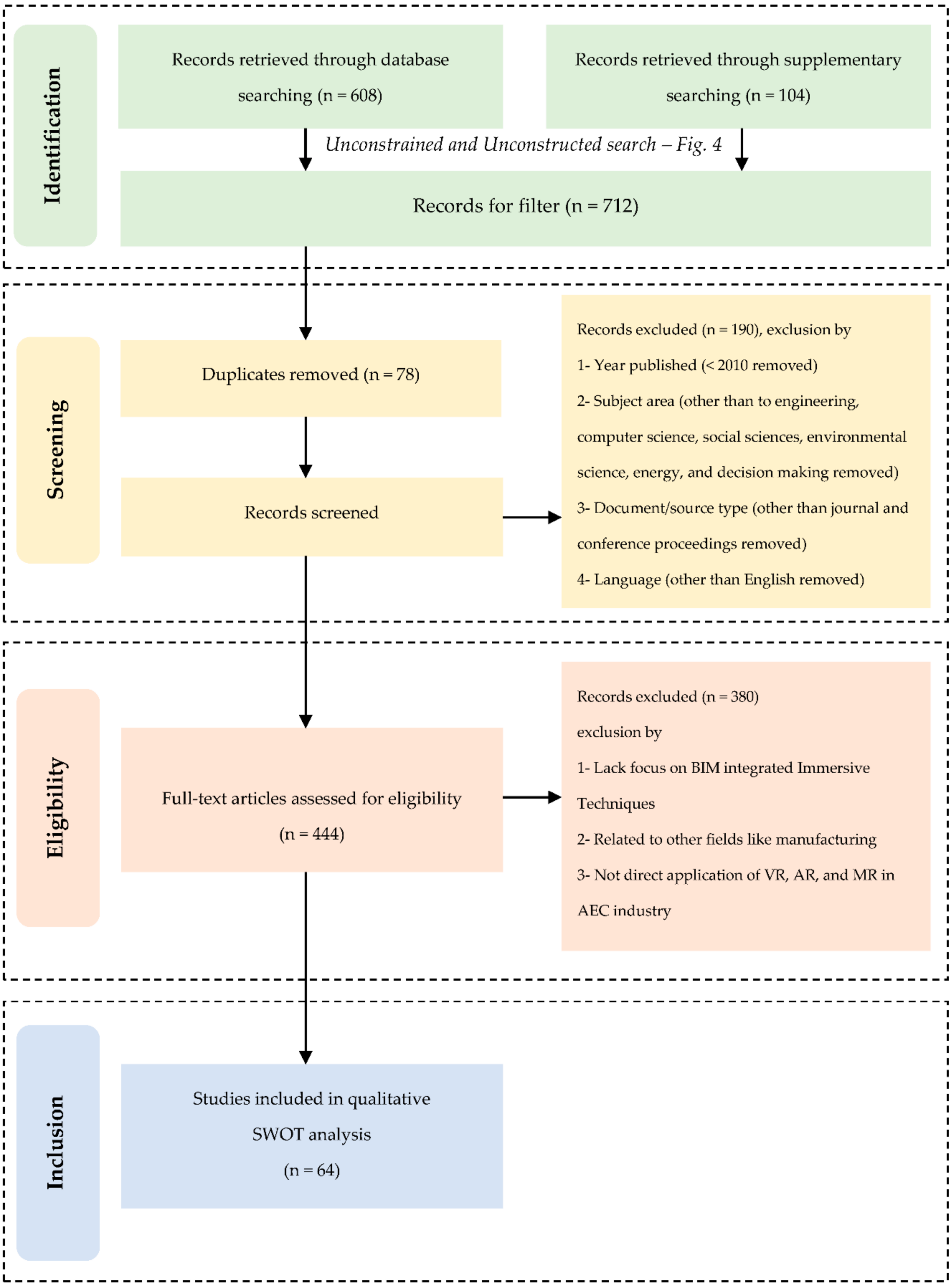


Figure 3. Research method for articles retrieval.

Identification—In this phase, the relevant records were recognized by including only peer-reviewed journal publications and conference proceedings. Conference papers are a convenient method to better understand what is ongoing in a field with up-to-date knowledge [164]. An unconstrained and unconstructed search was done initially for finding the relevant publications in the field of amalgamation of BIM and ImT's in the AEC industry. The relevant keywords were extracted based on publications investigation and authors' experience, following by a literature search, a two-way process, namely database search and supplementary search [165]. The keywords found during an unconstructed search assist in database searching, and a supplementary search was done based on publications from unconstrained and database search.

The keywords for this study were breakdown into BIM, Immersive Techniques, VR, AR, and finally MR for the AEC industry. After getting keywords from unconstrained and unconstructed searches, Scopus, which is considered as one of the authoritative database engines for academic data, was used. As compared to the Web of Science, Scopus has a wide variety of journals and publications [166]. Most articles in Web of Science are also included in Scopus. The data structure in Scopus includes literature types, authors, journals, keywords, abstracts, institutes, and references. Additionally, the Scopus API search gets shared results by using the Boolean syntax system. Keywords were input in Scopus search engine using the TITLE-ABS-KEY as follows: (BIM OR "Building Information Modelling*") AND TITLE-ABS-KEY ("virtual* reality" OR "augmented reality" OR "mixed reality" OR "immersive* technologies*"). Here "*" denotes a fuzzy type of search which includes words like model or modelling.

A total number of 608 articles (journal publications and conference proceedings) were found at this step of the search, and 104 articles were found from supplementary searching from famous journals of the field, as the concept of BIM and ImTs is significantly broad. Finally, 712 papers were retrieved from an unconstructed and unconstrained search. The process of unconstructed and unconstrained search is shown in Figure 4.

Screening—The filtering process in the screening stage of the search was then carried out in the following ways: 1. The limitation of the year was applied, and papers before 2010 were not considered as the relevant focus of this review study was towards the latest publications since the last decade. 2. Subject area was limited to engineering, computer science, social sciences, environmental science, energy, and decision making. Fields like medicine and business were not relevant to the study and were not considered. 3. Document and source type was restricted to conference and journal articles. 4. Papers not in English were removed, as they could not be reviewed in this study. Additionally, 78 papers were removed as they were repeating and duplicate in nature. 444 articles remained after this step for the eligibility phase.

Eligibility—The articles judged at this stage were 444 in number after the proper screening at an earlier stage. The filtering process in the eligibility stage of the search was then carried out in the following ways to remove the papers which: 1. Lack of focus on BIM integrated ImT's; 2. Were related to other fields like manufacturing; 3. Were not a direct application of VR, AR, and MR in the AEC industry and the concept of VR, AR and MR appeared just as a general term without having much stress towards the construction industry, resulting in an uncertain relation to the subject matter. Therefore, after passing the eligibility test, 64 articles remained for inclusion in the study to be further analyzed.

Inclusion—A total number of 64 articles remained for qualitative SWOT analysis in this stage to develop a fundamental understanding of their contribution towards BIM integrated ImTs in the AEC industry. The studies included applied multiple approaches to address their aims, including pilot study, case study, survey, and questionnaire, among others.

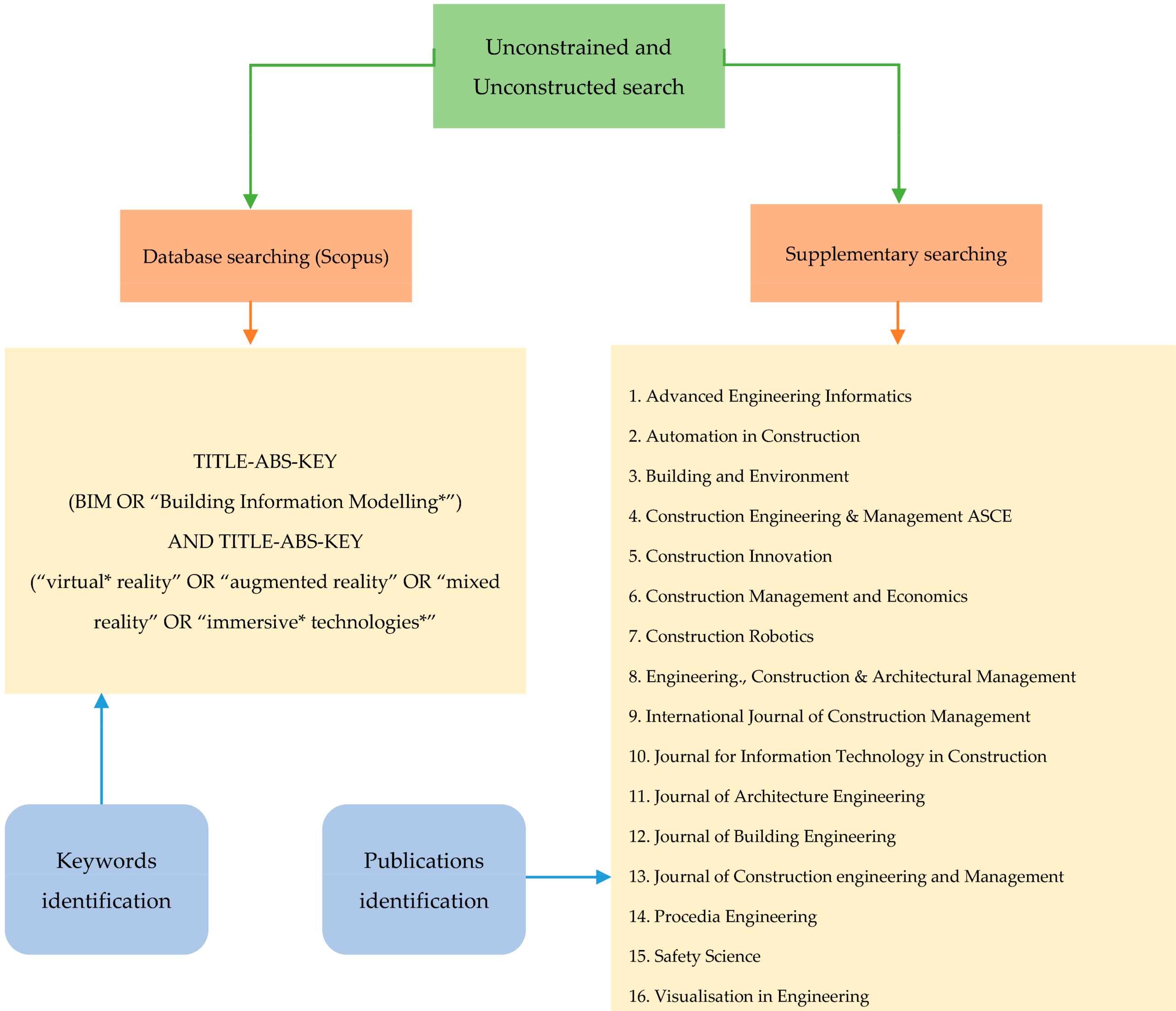


Figure 4. Identification phase of PRISMA method.

3.2. Bibliography Analysis

The 444 articles from the eligibility phase of the PRISMA protocol went through the bibliography analysis of the BIM integrated immersive technologies data set. The analysis identifies the keywords, themes of the dataset, contribution of countries, and major institutions in the current literature. Vos-Viewer [167] is the science mapping tool that was used to analyze the results, which is shown in Section 4 below.

3.3. Content Analysis

The rigorous review and study of the papers to form themes or domains is an effective way to monitor and structure the data for useful results [168]. The content analysis of all 64 papers was conducted for better synthesizing the qualitative data, and eventually, papers were divided into eight domains concerning the AEC sector, including client/stakeholder, design exploration, design analysis, construction planning, construction monitoring, construction health/safety, facility/management, and education/training. The results are discussed in Section 5. The domains are obtained as a result of themes generated in the scientometric analysis.

4. Scientometric Analysis

The scientometric analysis is used for mapping the scientific retrieved data [169] for evaluation of themes, dynamic aspects of data, and processing a wide range of information [170,171]. Furthermore, it gives impact measurement of journals and articles, institutes, countries, subjects, and keywords, which delivers the indicators for policy management across the subject removing subjectivity issues among the pieces of literature [172]. VOS-Viewer [167], Cite Space, the science of science tool, Bib Excel, and Gephi [173] are some of the common software's used to present scientometric analysis. The scientometric analysis is also used in review-based research for similar kinds of AEC topics, such as construction engineering and management [174], computer vision applications in construction [175], artificial intelligence in the construction industry [176], global BIM research [177], and interoperability issues in BIM [178].

Figure 5 provides an insight into the selected data from the eligibility phase of the PRISMA protocol showing the important keywords in the literature. The color of keywords denotes their likeness and interconnections, while a circle's size denotes its weight [176]. The larger the circle of an item, the higher the weight in the network. The distance attribute says the relatedness among the keywords, which is in terms of co-occurrence linkage. Therefore, if two keywords are close, the connection between them is stronger. Keywords usually have clusters associated with them, which shows the close interdependencies and relatedness among them [174].

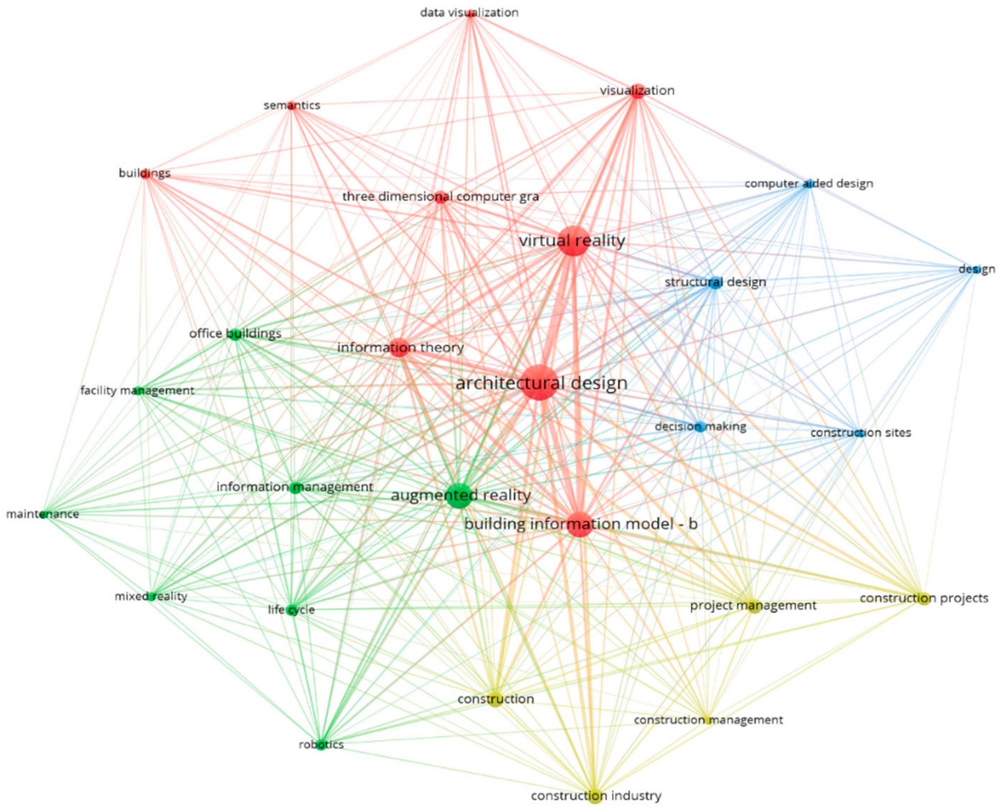
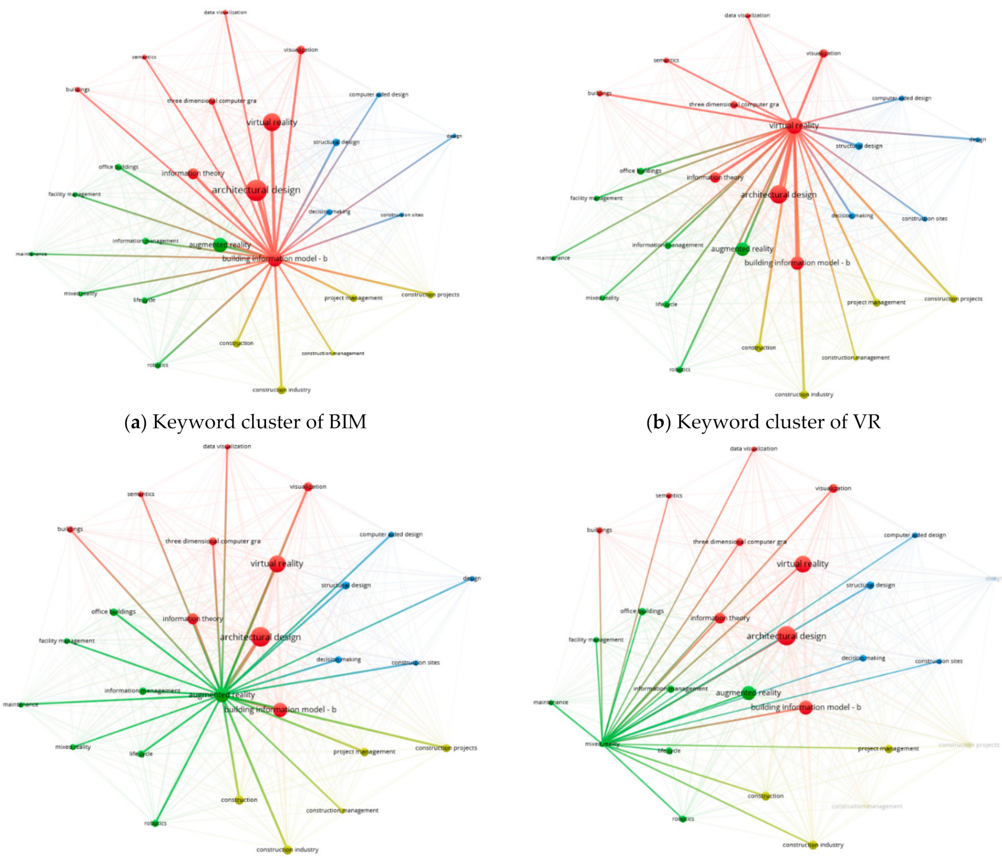


Figure 5. Visualizing the main keywords of the selected database. With the threshold co-occurrence of twenty, a total of 32 important keywords are selected.

Keywords co-occurrence provides the mental map of research topics in the field and facilitates the researchers to identify the relation between those keywords. Moreover, this mapping helps to identify the clusters and frequency of keywords addressed, which paves the way to fill in the gaps for future studies [179]. The information provided by the mapping is free of subjectivity and gives the freedom to not read the whole paper. Through the screening of titles, abstracts, and keywords of the papers, VOS-Viewer generated the co-occurrence of keywords. Figure 5 reflects the significant keywords and their relative clusters in the BIM integrated ImTs study. After setting the frequency of keywords to 20, 32 keywords are generated in the map. Additionally, there are no standard rules to set the frequency of the keywords' occurrence [180]. Further, the individual maps of four important keywords related to this study (BIM, VR, AR, and MR) are also displayed in Figure 6a–d. Moreover, the statistical description of keywords is shown in Table 4, including the occurrence and total link strength (TLS) of each keyword. The TLS reflects the number of links of a keyword with the other respective keywords. The analysis of the keywords occurred in Figure 5, and Figure 6 can lead to the following findings and discussions:

BIM, being the central core of the study, has the highest number of occurrences and TLS value, as shown in Table 4. Figure 6a shows the strong links of BIM with VR, AR, and architectural design, reflecting the significant importance of BIM knowledge to achieve and perform immersive studies. Other than this, BIM has strong links with small clusters like construction management, design, visualization, information theory, and information management. However, the process of MR is still in its nascent stage across the AEC industry, which is clearly visible with its link to the BIM process. The evolution of BIM is significant in the industry, and with the likes of integration with simulations, IoT and Artificial Intelligence processes, it is leading to the Digital Twin process [180].



(**a**) Keyword cluster of BIM (**b**) Keyword cluster of VR

(**c**) Keyword cluster of AR (**d**) Keyword cluster of MR

Figure 6. Cluster of four significant keywords (BIM, VR, AR, and MR) in the study.

Table 4. Top keywords in the BIM integrated Immersive Technologies (ImTs) study.

Keywords	Occurrences	Total Link Strength
Building information modelling	459	2287
Architectural design	362	1697
Virtual reality	272	1216
Construction management	246	1390
Augmented reality	168	784
Information theory	106	667
Visualization	87	510
3D computer graphics	74	413
Project management	53	330
Structural design	50	282
Facility management	44	268
Information management	41	258
Office buildings	40	240
Robotics	35	210
Lifecycle	34	214
Decision making	34	209
Mixed reality	24	131
Semantics	22	106

Figure 6b shows the connections of VR with other keywords. The link with visualization, architectural design, information theory, and 3D computer graphics is strong. This reflects that VR is mainly used as a visualization enhancing tool by the clients and other stakeholders of the industry. However, it also links with the mini clusters of construction management, facilities management, and design process. However, the low connection strength of VR with other mini clusters other than visualization is due to low sensitivity, and cognitive and perceptual points delivered by the VR process. This causes low adoption in the industry works, especially requiring accuracy and precision. This requires developers and technology drivers to develop more refined hardware and software solutions providing experiences in a more immersive, holistic, tangible, realistic, touchable, and perceptible way [181].

In comparison to VR, AR has low occurrence and TLS values but has strong connections with the facilities management cluster. The integration of an AR environment in BIM can facilitate the data in a more meaningful way, thus changing the outcome from a static nature to more real-time visualization, and hence providing seamless site management. The vast amount of data and interaction involved in the construction project can be accessed easily by AR, thus making it an important and seamless way of detecting aspects involved with the view of a user. This can be viewed in Figure 6c where AR has strong links between the construction management cluster and the decision-making cluster. Although AR is the most effective way to encourage the 3D outputs to date and systems, which have become advanced in recent years, the sense of nausea, claustrophobia, and motion sickness still occurs on a certain scale which should be a concern for the researchers and industry persons in the future [10].

Finally, MR has the lowest occurrence and TLS values among the three ImTs as seen in Figure 6d, and has links with only the facility management side of the AEC industry. This lack of studies is due to the newest nature of this immersive technique, which still needs the latest solutions to make it leapfrog in the AEC industry [182]. Corresponding techniques like better localization, improved display, integrated interaction, increased data storage, and collaboration can escalate the maturity of MR applications in the AEC industry [36]. Solutions like cloud computing, 5G technology, and AI techniques will increase the usage of MR applications in large-scale construction projects [36]. On a rudimentary level, MR will be embraced by the firms in the future at a vast level as the onset of Construction 4.0 will digitalize the industry, supplying a paradigm shift in the working culture of AEC firms. Additionally, the future way will be a Hybrid Reality, allowing the merging of all the realities into one joint system and allowing a person to switch back and forth into the real or virtual world depending upon the usage [182].

5. SWOT Analysis

5.1. An Overview of the Application of Immersive Technologies in the AEC Industry

Mainly used for business areas, a SWOT analysis helps to frame the factors that can affect any company's market value, while giving future predictions too. However, it has been used for other industries as well, like career planning, urban renewal projects, web design areas, and academic research centers [183], among others. Additionally, it is best suitable to find the internal strengths and weaknesses of a certain unit along with citing the trends (opportunities and threats) which can be faced in the future. Figure 7 shows the pictorial representation of domains obtained as a result of themes generated in the scientometric analysis. Each domain reflects the use of ImTs linked to themes. The research domains obtained are structured based on existing research to facilitate the understanding of ImTs to give an overall picture of the subject matter and further state recommendations and future directions based upon the rationale. Table 5 provides the share of 64 articles for each domain and the percentage contribution from the articles analyzed for this study with reference for each paper.

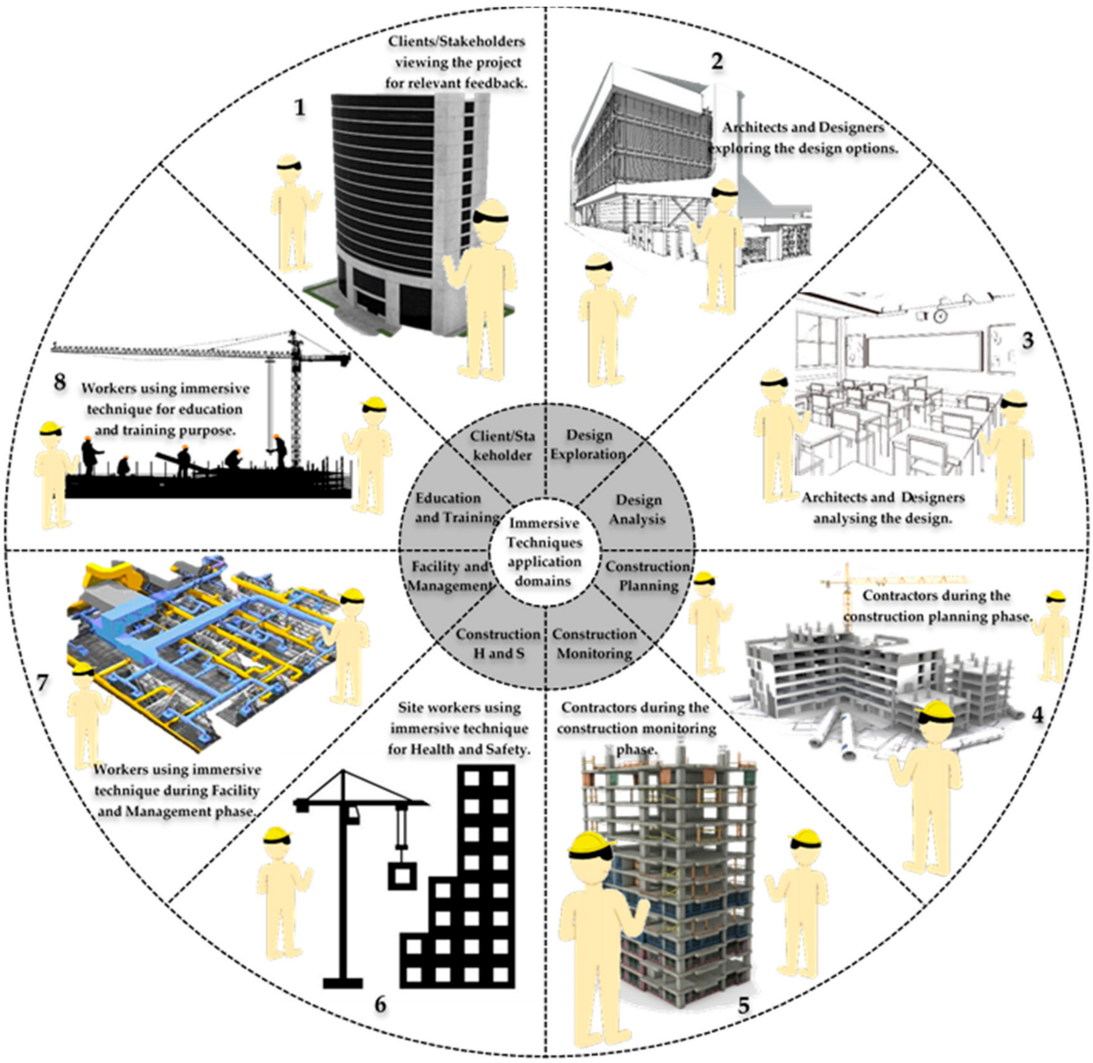


Figure 7. Pictorial representation of each domain work with ImTs in the AEC industry (NOTE: All the images are under creative commons license).

Table 5. Percentage articles of each research domain with references.

Research Domains	Code	Number	Percentage	References
Client/Stakeholder domain	RD-1	5	8	[184–188]
Design Exploration domain	RD-2	9	14	[42,49,67,189–194]
Design Analysis domain	RD-3	9	14	[6,53,99,147,195–199]
Construction Planning domain	RD-4	6	9	[21,22,57,61,200,201]
Construction Monitoring domain	RD-5	6	9	[123,124,141,202–204]
Construction Health and Safety domain	RD-6	8	12	[129,150,205–210]
Facility & Management domain	RD-7	9	14	[18,136,189,211–216]
Education & Training domain	RD-8	12	20	[20,91,93,95,108,145,153,217–221]
Total		64	100	

It is evident from Table 5 that the design exploration domain and design analysis domain share an equal percentage, which clearly shows that the majority of ImTs in the AEC industry are applied in the design phase of a project. ImTs can prove to be an asset in the initial phases of the design for viewing the feasibility of different design options by allowing different stakeholders to visualize them [99,222]. It gives a clear picture of the pros and cons of the designed space by viewing it from ImTs, which also helps in exploring different options and analyzing the outcome for the smooth working of the project.

On the other hand, the health and safety of the construction workers at the site have always been an issue worldwide [223]. The damage caused by improper health and safety measures is irrevocable and sometimes leads to fatal accidents. In this regard, ImTs help in finding the potential threats which can occur at the site prior to their actually happening, thus reducing the chances for any issues to a large extent [209]. Therefore, the percentage of research about construction health and safety domain contributes largely to the research and will continue to depend on ImTs to create the simulated environment for the better judgment of health and safety issues at the site.

However, the percentage share of client/stakeholder domain, construction planning domain, and construction monitoring domain is comparatively low with respect to other domains, which shows that research needs to increase in these areas. The different nature of the client makes it difficult to make him/her understand the clear picture of the project due to technical factors involved in a project [224]. Additionally, options presented by the design team make it unclear for a client to judge a better outcome for his facility. However, with the growth of ImTs and the amount of interaction they can provide, it has become a trouble-free task for a client to understand the technical know-how of the project, which results in better satisfaction and outcome of the project [225]. On the other hand, the reason for a low contribution of the construction planning domain and construction monitoring domain may be due to many reasons. As the construction site involves many workers working at different tasks simultaneously, it is, therefore difficult to provide each team with access to immersive techniques due to capital issues [104]. Moreover, planning and observation of a construction task involve many miniature details where the approach of a worker becomes difficult, thus hindering the use of ImTs at that situation and place. However, in recent times, the integration of ImT's with technologies like drones has made access to remote locations at a site workable, and research in this direction will increase in the future [226].

Talking about the facility and management domain, the research in this direction is growing as ImTs deliver useful information for the workers to run and uphold the various facilities at a site remotely as well as in-person [213,215]. Supporting building maintenance work, repair, inspection, providing technical information to workers, and assisting in assembly/disassembly tasks are features provided by ImTs [213]. Lastly, a huge amount of research is inclined towards the education and training domain as the ImTs can deliver realistic scenes and scenarios for the workers to develop and gain the required skills and information needed at a site [227]. Moreover, the cost of training and educating the workers can be reduced with the help of ImTs by simulating the environment likely to occur at a site, thus reducing chances of potential threats, and resulting in health and safety issues.

Based on the contribution analysis of ImTs for various domains, the word cloud for the three most researched domains is presented in Figure 8, which reflects the most repeated keywords for the data set and gives the overall ideas and focus for the future. For example, words like safety, hazard, and workers, along with training and virtual, are relevant for the health/safety domain. They are the most researched terms and themes in the context of safety in construction [209]. Similarly, words like education, students, training, and learning, along with virtual and reality, frequently occurred in the education/training domain as the understanding of the tasks in a virtual environment is preferred for both construction students and professionals [95,227]. Finally, the keywords that occurred the most in the facility/management domain are maintenance, management, assembly, facility, and information, as these words form the basis of the facility management (FM) process through the integration of ImTs.

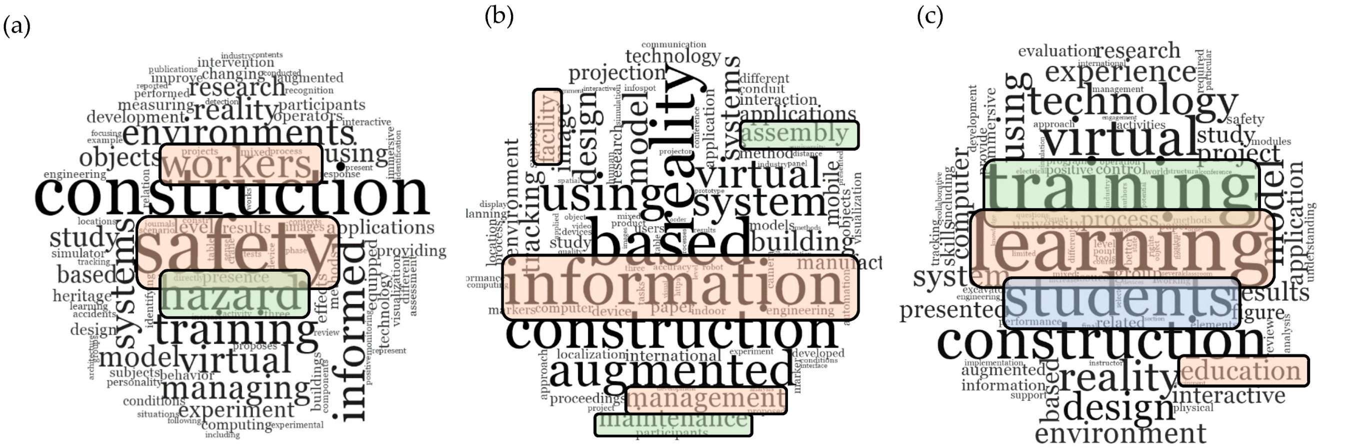


Figure 8. Word cloud for three researched domains (**a**). Health and Safety, (**b**). Facility and Management, (**c**). Education and Training.

A critical review of each domain is done based on the SWOT (Strength Weakness Opportunity and Threat) analysis (see Tables 6–9), highlighting ImTs integration with them to give a clear picture of each domain. It provides the roadmap for future researchers and industry people to better strategize the adoption plans of ImTs for their respective interests. Finally, based on different analyses and research backgrounds, key emerging trends have been highlighted and discussed for future research, and development efforts needed to be focused on ImTs with BIM. The integration of BIM and ImTs at different phases of the project can improve productivity, saving costs and time, along with improving safety and quality.

Table 6. Strengths of immersive techniques for AEC/facility management (FM) domains.

Strengths			
RD-1 Client/Stakeholder	**RD-2 Design Exploration**	**RD-3 Design Analysis**	**RD-4 Construction Planning**
·Better feedback ·Client engagement ·Realistic experience ·Improved marketing ·Selection of contractors ·Social and emotional impact ·Pros and cons of design ·Saves travelling time ·Future interventions ·Reduced risk and cost ·Ergonomic testing ·Buyer experience	·Easy review ·Better update ·Design decisions ·Avoids remodelling ·Spatial understanding ·Size and scale knowledge ·Interior design review ·Barrier free design ·Risk identification ·Clash detection ·Smooth editing	·MEP knowledge ·Clear design intent ·Review and analyze design ·Luminance understanding ·Daylight presence fluency ·Review of surface texture ·Potential risk knowledge ·Analyze spatial nature ·Design flaw reviews ·Window wall ratio ·Thermal analysis	·Less errors ·Better schedule ·Facilitates planning ·Helps waste reduction ·Material procurement ease ·Ergonomic scale testing ·Better material choice ·Reduces conflicts ·Task sequencing ·Reduces cost
RD-5 Construction Monitoring	**RD-6 Construction H/S**	**RD-7 Facility/Management**	**RD-8 Education/Training**
·Real time site status ·Reduces error at site ·Human scale observation ·Detection of schedule lag ·Aid construction monitoring ·Remote progress checking ·Assists in virtual guides ·Workers competency ·Avoids possible risks ·Reduce overall cost ·Lowers mistakes ·Save man hours	·Reduces risk ·Risk recognition ·Safety inspection ·Evacuation simulation ·Increases productivity ·Human building interface ·Avoids potential threat ·Hazard identification ·Less material waste ·Fall risk simulation ·Saves time and cost	·Repair processes ·Assembling tasks ·Disassembling tasks ·Tedious task easiness ·Supplying visual cues ·Remote operation facility ·Technical information ·Risky tasks simulation ·Building maintenance ·Built asset knowledge ·Reduction in risks ·Objects tracking	·Increases skill ·Ease of simulation ·Awareness of tasks ·Fall hazard scenarios ·Scenario based learning ·Easy hazards training ·Reduce travelling cost ·Spatial understanding ·No material waste ·Aids student skill ·Low capital

Table 7. Weaknesses of immersive techniques for AEC/FM domains.

Weaknesses			
RD-1 Client/Stakeholder	**RD-2 Design Exploration**	**RD-3 Design Analysis**	**RD-4 Construction Planning**
·No standards ·Location errors ·Motion sickness ·Difficulty in sharing ·High hardware price ·Substantial time required ·Inaccurate registration ·Movement constraints ·User interface issues ·Fickle luminance ·Isolation feeling ·Software costs	·Low quality ·Low collaboration ·Difficult archive process ·Content creation difficulty ·No complete hardware suit ·High skillset required ·Model linkage obstacle ·Model size constraints ·Interoperability issues ·Lack of standards ·Short battery life ·IP issues	·Cost of setting up ·Low battery life ·File uploading time ·Data storage difficulty ·Changing while viewing ·Movement limited by wiresInternet bandwidth issues ·Content creation is tough ·Time required is high ·No complete package ·Time lag in viewing ·Cognitive issues ·Motion sickness	·Lack of accreditation ·Hardware requirement ·Metadata viewing issues ·High level of investment ·Issues in interoperability ·Number of devices required ·Less battery life hindrance ·High expertise required ·Acoustical senses issues ·Schedule upgradation ·Model update issues ·Low visual senses
RD-5 Construction Monitoring	**RD-6 Construction H/S**	**RD-7 Facility/Management**	**RD-8 Education/Training**
·Fragile when using ·Disorientation issues ·Low resolution display ·Additional cognitive load ·Unfit to wear with hardhat ·Cost of adoption for many ·Site internet limitations ·Battery drains quickly ·Uncomfortable nature ·File size limitations ·Job security fear	·Mobility issues at site ·Location errors issues ·Requires steep learning ·Depth analysis problem ·Chance of physical impact ·Lack of current standards ·Luminance inconsistency ·Sensory needs adds cost ·Feebleness while at site ·Meta data accessibility	·Data archiving issues ·Low level of accuracy ·Low contextual awareness ·Long use cause nausea ·Object registration issues ·Inconsistent battery life ·Headsets hard to wear ·High skill required ·Low update speed	·High training cost ·Evaluation process ·Less skilled trainers ·Difficulty in content creation ·Low government partaking ·Need for powered machinery ·Lack of systematic approach ·Lack of social interaction ·Fragmented nature ·Lack of standards

Table 8. Opportunities of immersive techniques for AEC/FM domains.

Opportunities			
RD-1 Client/Stakeholder	**RD-2 Design Exploration**	**RD-3 Design Analysis**	**RD-4 Construction Planning**
·Agile gadgets ·Real scale built asset ·Wireless technologies ·Affordability in price ·Scalability and flexibility ·Advances in techniques ·Productivity enhancement ·Organisation reputation ·Spatial comprehension ·Devices comfortability ·Return on investment ·Escalation in business ·Visual realism	·Knowledge sharing ·Software knowledge ·Common data formats ·Resolve interoperability ·Integration with gaming ·Content creation skills ·Data trust with each other ·Data transfer classification ·Enhanced virtual meetings ·Cloud based management ·Avatars communications ·Synchronisation of data ·Proof of concepts	·Haptic control boost ·Olfactory simulations ·Sustainable experiences ·Sense and feeling of space ·Visual cues enhancements ·Advance user experience ·Standardised approaches ·Microclimate experience ·File size enhancements ·Better headsets for use ·Situational awareness	·Schedule prediction ·Utilisation of resources ·Non graphical data skill ·Enhanced collaboration ·Adding cyber physical order ·Adding RFID and GIS system ·Constructability analysis ·Cloud based interactions ·Complete set up package ·Utilising 5G technology ·Mixing computer vision ·Better delivery of asset
RD-5 Construction Monitoring	**RD-6 Construction H/S**	**RD-7 Facility/Management**	**RD-8 Education/Training**
·Network latency boost ·Contextual procedures ·Machinery teleoperation ·Remote progress monitor ·Integrating computer vision ·AI mixing for well knowhow ·Safety approved hardware ·Drone technology mixing ·New simulation methods ·Better resolution devices ·Light weight of headsets ·IoT sensors integration ·Increased field of view	·Sensory tools boost ·Headsets battery life ·View range of headsets ·Enhancing image of AEC ·Boosts cognitive behaviour ·Tracking device integration ·Better metadata integration ·Better site emergency plans ·Knowing workers stimulus ·Better job hazard analysis ·Gaming industry mixing ·Controlling technologies	·Boost in field of view ·Integration with BMS ·Increase in battery life ·Information accuracies ·Data sharing standards ·Boost for colder site regions ·Better wayfinding methods ·Integrating drone and UAV ·Low-cost of hard/softwares ·Lift in common platforms ·Enhanced data access	·Reduces risk fear ·Clarification in design ·Motivates new students ·Improves industry image ·Costs saving on materials ·Boosts sustainable learning ·Make student industry ready ·Enhances worker's ability ·Cost saving on machinery ·Cognitive enhancement ·Safe learning platforms ·Learning by doing

Table 9. Threats of immersive techniques for AEC/FM domains.

Threats			
RD-1 Client/Stakeholder	**RD-2 Design Exploration**	**RD-3 Design Analysis**	**RD-4 Construction Planning**
·Capital risk ·Risk of injury ·License agreements ·Detrimental health effects ·Intellectual property rights ·Rapid technology change ·Outdated technique issue ·Legal fraud issues ·Legal liabilities	·Job security issues ·Legitimacy of content ·Unsustainable practice ·Overlooked determination ·Risk of data fragmentation ·Long use cause bad health ·No standards cause risks ·Hefty cost involved ·Security of data	·Glare issues ·Motion sickness ·Striking graphics ·Content fragmentation ·Luminance affects eyes ·Lack of near awareness ·Labour duplication ·Visual discomfort ·Low field of view	·Disintegrated use ·No safety guidelines ·Metadata susceptibility ·No liabilities in contract ·Lack of multiuser interface ·Disjointed consumption ·Less trained workforce ·Risk of cyber hacking ·Data vulnerability ·Threat of job loss
RD-5 Construction Monitoring	**RD-6 Construction H/S**	**RD-7 Facility/Management**	**RD-8 Education /Training**
·Lack of sensory inputs ·Nearby cut off in VR ·Lack of open standards ·Job loss threat in workers ·Situational warnings absent ·Lack of multimodal senses ·Unequipped XR devices ·Network latency at site ·Imperviousness in data	·Flashing lights ·VR blocks near view ·Nausea among workers ·Dizziness when used long ·Seizure issues for workers ·Vulnerability to hackers ·Lack of content warning ·Sudden graphic change ·Cybersecurity issues ·Disorientation issues	·Motion sickness ·Fragmented supplies ·Lack of social interaction ·Situational awareness risk ·Long use cause vision snags ·Cognitive load by focussing ·Rough use cause price issue ·Striking graphics concern ·Difficult with hardhats	·Headsets strains ·High cost hindrance ·Technology change barrier ·Social interface discord ·Lack of many educators ·Uncertainty and disbelief ·Time required is high ·Fragmented content ·Stress on students

5.2. Limitations of the Study

The limitation of this research study is the amount of sample collected for this study. The search engine Scopus was the only source taken for the sample, not considering other search engines present in the research domain like Google Scholar and Web of Science. Scopus is the largest database of peer-reviewed literature. The data collected in this study is sufficient to encompass the main body of knowledge in this field. However, future studies related to this topic may include other sources and databases to have more consolidated information to achieve more comprehensive results.

6. Recommended Research Directions

Based on the content analysis and SWOT analysis of research domains for the AEC industry using ImTs, future directions are summarized in Table 10 below. Three broad categories were found with five subcategories, each to lay focus upon for the future work required in ImTs and BIM integration for the AEC sector. The directions are in the context of requirements of ImTs devices in the future, how the graphical/non-graphical data need to enhance, and finally, the responsive/integrative prospects. The distribution of each category further into five subcategories will pave the way for researchers and industry professionals to upskill those areas to extract superfluous rewards.

Table 10. Limitations and future needs comprehensive outline.

	User Centered Comfort Devices	View Field and Battery Capabilities	Accuracy and Tracking Process	Considerable Storage Capacities	Enhanced Positioning and Mapping	
Limitations	1. Potential threat chances due to design discrepancies are common. 2. Level of discomfort often arises after prolonged usage of the devices. 3. Not robust for site use as site work often includes unwanted situations. 4. No standards for site use specifically. 5. Uncomfortable for long use is there. 6. User sense limitations are there. 7. Workers distraction is common. 8. Increase in the cognitive load of the user or workers after certain time. 9. No warnings near the likely threats.	1. Hinders postural stability of the end user in most cases utilized. 2. Low view field degrade sense of presence in the XR scenario often. 3. Low self-motion perception especially in the VR environment. 4. Battery lasts only 20 to 25 min when fully charged is a concern. 5. Heavy use can drain the battery quicker as construction sites mostly involve a long man and task hours. 6. Unreliable for long site works requiring consistency in the tasks.	1. Trackers used in the devices are not robust enough to track tricky geometry present. 2. Accuracy of devices is not up to mark. 3. Underground areas need accuracy to avoid any risk, ex: piping installation mechanism which often lacks in devices used across. 4. Plane geometry difficult to track as they lack detail aspect of tracking points. 5. Unreliable in risky areas due to the presence of unwanted objects and items. 6. Level of uncertainty is unavoidable in most cases as the process requires more robust tactics and strategies for the users.	1. Limited ability for model storage is a concern in XR devices at present. 2. Difficulty in storing complex BIM models due to large dataset in them. 3. Processing capacity is usually low, truncated and time taking usually. 4. True depiction of BIM models becomes as arduous task as the visualization process becomes broken due to presence of large number of objects and images involved. 5. Presence of huge metadata related to objects is a cause of problem.	1. Lack of positioning systems is present in complicated BIM models. 2. Incapable features of accelerometers, magnetometers, and gyroscopes. 3. Insufficient capabilities to map changing site environment around. 4. Limited strident data for sensing is an issue of concern which is least available now for most of the XR devices. 5. Not many localization techniques available for successful positioning of rich data available for the combined and consolidated BIM models.	**Immersive Techniques Devices**
Needs/Future	1. Identification of discomfort sources from the devices for betterment. 2. Devices should be capable of mitigating rough site conditions present. 3. Assessment of devices in different conditions of site is required. 4. Alerts for health and safety to users. 5. Risk mitigation from devices by analysing archived data will benefit. 6. Tracking data from eyes shall be analysed for better comfort to the user. 7. Warning recognition of objects in the AR environment without the presence of markers shall be facilitated in devices.	1. Enhancing field of view by capitalizing resolution studies and scene content variations in the devices. 2. Increase in power abilities, especially for use at remote site conditions. 3. Connected device through external storage mediums to minimize consumptions and problems of storage. 4. Easily replaceable batteries should be facilitated for smooth working at long hours at site without hinder. 5. Implementing laser technology to achieve 120° human comfort non hindered view at the related area.	1. Real time uncertainty level of devices should be focused to avoid discrepancies. 2. Integrated trackers should be facilitated with marker and marker fewer options. 3. Explicit depiction of object and its information through enhanced scanning. 4. Scanning techniques accuracies of devices to explore alternate dimensions for an object to bring more depth in the accuracy. 5. Studies focusing on uncertainty levels for immersive devices should be carried out 6. Computer vision techniques should be integrated for better results in the outcome.	1. Liberty to upload view range BIM models for uninterrupted sight. 2. Vigorous means to activate view range model at vision for objects. 3. Freedom to change the level of detail for the BIM model to compromise the size variations for different situations in the real time to ease the process. 4. View range options for near and far objects in the model should be there. 5. Enhanced data processing techniques should be used and incorporated based on various programming procedures.	1. Need for correct objects and image augmentations for users and workers. 2. Mirror worlds phenomenon can blanket the physical space around. 3. System should guide workers about egress routes when in danger or unwanted situation occur during work. 4. Identification of materials, equipment, and assets around the site to avoid any discrepancy should be facilitated. 5. Betterment through enhanced Wi-Fi signals at the site and other magnetic field technologies concerning AEC.	

Table 10. *Cont.*

	Spatial-Temporal Visualisation	Data Record Capabilities	Standards Framing	Cybersecurity and Privacy	Integration with Other BS Systems	
Limitations	1. Data analysis and visualisation restricted to 2-D interface only. 2. Absence of physical world related reference for the data is an issue. 3. Original context, usage and interpretation of data for the objects is significantly low and below par. 4. Spatial and temporal values misses out in rectangular window type template. 5. Integration lack between model, parametric data and relevant objects with time and senses.	1. Lack of archived data keeping for instructional purposes which can be utilised in the future. 2. User experience in XR environment is difficult to store for future. 3. Only set of authoring software and applications can be used for assessment which is a barrier. 4. Although BIM model is saved, but the real time experience of user is lost, rather only first person recording is preserved in the current scenarios.	1. Lack of standards for XR environment well suited for construction industry. 2. As AEC got IFC, immersive environment lacks compatible format for XR software and tools which makes interoperability issues. 3. Although, few tools provide some extent of conversion, but the standard approach is missing. 4. Object parameters issues along with it's material, texture and metadata is still a challenging affair.	1. Trickery holograms and bodily harm caused during immersion is a risk for the end user in usual cases. 2. System scope and functionality challenges such as conflict between input sharing and output devices. 3. Access control complexity for sensory data is a privacy concern. 4. Problem of unwanted virtual content which can cause clutter, obstruction and inappropriateness in the XR environment, is an issue.	1. Limited integrative approaches available for seamless mixing. 2. Also, the data storage capabilities of existing XR devices is relatively low to include data from other systems concerning AEC industry. 3. The issue of confined practise maintained by systems is also a barrier to integrate other scheme. 4. Collaboration among stakeholders concerning development of tools is absent and need to be more robust.	Graphical and Non-Graphical Data
Needs/Future	1. Task specific data visualisation should be carried out in the XR environment to relate the complexity in the sector. 2. New immersive displays showing data in spatial-temporal context should be researched. 3. Amount of intuitive alteration developed by visualisation needs to be find out and rectified. 4. Need to develop an integrated approach of visulaising metadata oroginated from objects, immersive objects and information about them.	1. Vital to record user knowledge while doing a task to experience the same situation by others to avoid errors. 2. Research based on archiving immersive data, it's recording and sharing should be promoted among the various stakeholders concerned. 3. Big data visualisations methods such as dynamic projection, interactive filtering, interactive distortion and interactive combination shall be used for recording best experiences.	1. An interoperable approach between BIM standards and presently limited XR environment standards need to establish for smooth facilitation. 2. Recently in 2019, Open XR, a royalty-free open standard for XR platform and devices have been developed, which allows design and use of any platform for an integrative approach. 3. Overall, the data exchange between BIM and XR standards still needs to be more robust and versatile in the sector and needs to be researched more.	1. Privacy from bystanders, invasive applications and holograms need to be addressed for generating non hindered information flow. 2. Access control to objects, preventing unwanted content, making access control UI's and having personal space in XR environment need to be studied. 3. A guideline framework concerning privacy issues needs to be established for the eight domain cases mentioned in the SWOT analysis for the construction industry.	1. Need of seamless integration with Building Services systems, Building Management Systems and other BIM related solutions and systems. 2. Easy or no programming skills such as visual scripting should be promoted for mixing BIM data with other built environment systems. 3. Tools like ladybug, cove and similar to them should be promoted and easy plugins of such kind of tools and mediums should be developed in the future for better outputs.	

Table 10. *Cont.*

	BIM Model Reform in Real Time	Simulations Predictions	Robotic Teleoperation	Multiple Sensory Integration	IoT Devices Combination	
Limitations	1. Real time BIM model change is still an arduous task in XR environment. 2. Difference in a model for BIM and XR space due to the directly relating issue makes it difficult to update. 3. Changes are done in material, texture and other object-related parameters for taking BIM model in XR space also brings latency. 4. VR lacks changes made to depict in BIM model and AR lacks presenting virtual objects used to reflect back in a precise manner.	1. Currently XR devices are unable to provide predictions and about future situations likely to be encountered at the site. 2. The simulations and optimisations process for a project needs to be analysed separately and on 2-D medium which lacks a huge amount of engagement for stakeholders. 3. AEC project requires many what-if scenarios-based studies which are currently not in the scope of XR devices and environment.	1. Research in robotic teleoperation for the AEC industry is still in its novel form. 2. The cost factor for the tele-operation through XR devices is significantly high for the AEC sector. 3. Although robotic arms and skeletons are available for use by workers but teleoperation still needs to find a way. 4. AEC industry possesses various risky and unexperienced zones, which can be troublesome for the teleoperation process also at times.	1. AEC sector lacks integration of sensory inputs and outputs in the XR experience. 2. Most of the use cases have the vision, auditory and, to some extent haptics. 3. Other senses like gustation, olfaction and thermoception are still not researched for use in the AEC industry. 4. The limitations in size, weight, memory and processing power of the XR devices also make it tough to include all other important senses for use in many domains in the AEC industry.	1. Lack of system capabilities of XR devices still repudiates IoT integrations for AEC industry for better outputs. 2. Biggest challenge is to assimilate the BIM information without any redundancies in the applications currently present in the market. 3. Studies related to IoT integration with XR environment are present, but they lack seamless flow between the two. 4. Currently, XR devices lacks such robust systems which can store enormous real time data from IoT's.	**Responsive and Integrative Prospects**
Needs/Future	1. A two-way amendment between the BIM model and the XR environment need to be established in real-time. 2. Dissimilar file and database system makes management for BIM and XR environment a strenuous task. 3. The onset of solutions like Enscape, Lumion, Twinmotion and IrisVR can leverage this problem to some extent but a holistic approach in this direction is still need to be researched and focussed.	1. Need development for XR devices and environment which can provide various predictive states for the AEC project such as time, cost, hazards, safety issues, loads etc. 2. Big data and AI features will be required to enhance the current XR devices to have a predictive and prescriptive analysis of such kinds. 3. Also, the processing power needs to be escalated for providing simulations and optimisations for better decision making of a project.	1. Teleoperation processes as related to physical operation are notably safer in the AEC industry, which has hazardous, risky, and detrimental environments around many tasks faced by a worker. 2. The future potential of teleoperation in the AEC sector will rely upon better sensory integrations and a combination of human & robotic capabilities to enhance the physical and virtual worlds. 3. The risk and safety factors for most of the used cases will be minimised.	1. Need for integrating different sensory inputs to deliver intuitive communication between objects and users in AEC tasks. 2. Addition of senses in the XR experience will lower the cognitive load of a user along with providing safety in the tasks. 3. Various AEC tasks involving health and safety issues can be minimised through the integration of many senses; they will provide a natural environment and the future requires proper engagement.	1. Enhanced decision-making for the site operations with the inclusion of IoT sensors data with XR devices. 2. Automated site monitoring along with materials and equipment checking will get facilitated. 3. Accuracy in the assessment of task including risk factor as the information received will be updated and revised. 4. Development needs to be directed towards finding new data outlines, schemes, technologies, and methods for seamless integration.	

7. Conclusions

This review presented a study on the integration level of ImTs with BIM in the AEC industry. The ImTs, which include VR, AR, and MR, have shown colossal benefits in the way AEC projects are designed, constructed, and managed. This review leveraged different analysis methods to present the literature landscape in the field of ImTs relevant for academicians and industry professionals. The outcomes of this review are 1. defining the literature of ImTs for different AEC domains, 2. doing a SWOT analysis of ImTs in each domain defined, and 3. highlighting current limitations and proposing future needs for successful adoption and implementation of ImTs. The research included the PRISMA protocol for collecting 64 articles for a critical review out of 444 articles from the Scopus search engine related to BIM and ImTs. The content analysis of all 64 papers was done for better synthesizing the qualitative data, and eventually, papers were divided into eight domains, which are governed in the AEC sector. The domains are client/stakeholder, design exploration, design analysis, construction planning, construction monitoring, construction health/safety, facility/management, and education/training.

A SWOT analysis of each domain has been performed to present the discrepancies and to give a clear picture of each domain. The overall adoption and implementation of ImTs have been found low, with few domains using it to a large extent compared to others. It was found that the design review and design analysis domain have been the most used cases. ImTs offers a support system for design decisions and the provision of analyzing the design outcome before the construction process starts. For construction planning and monitoring domains, opportunities to view and predict a complete forecast of the construction schedule is facilitated through ImTs. Moreover, ImTs deliver the utilization of resources over a due course of time and the need to deliver more contextual procedures for information to workers. The other domains like health/safety, facility/management, and education/training are also reaping the benefits through ImTs. It enhances better communication at a site between workers and construction managers. Additionally, workers leapfrog their ability to track learning progress based on the interactivity with the tools and techniques in respect to physical training.

Finally, research directions for future growth on the adoption and implementation of ImTs are presented. The directions are based on proposing three categories, namely immersive devices, graphical/non-graphical data, and responsive/integrative processes, along with subcategories for each category. In terms of technological advancement, bandwidth from fifth-generation (5G) technology will increase the efficiency of ImTs to offer remote collaborations better. The cloud-based ImTs driven by 5G network and edge cloud technologies will enhance the process of application development. It will escalate a clear understanding of the information between the physical and cyber worlds. Better user interface and interaction along with real-time training at a site to increase awareness will become the new normal. Real-time perceptive responses based on feedback will be strengthened because of better cloud computing and networking quality. BIM integration with cloud ImTs will increase the explicitness of task interdependencies, as the virtual and physical data will be shared seamlessly. The integration of BIM and ImTs will deliver novel workflows and escalates the AEC industry as technology-driven.

The significant contribution of this review is that it grouped the literature on ImTs in AEC domains for better understanding the factors limiting and driving in each domain. However, the applications of immersive technologies along with BIM can be explored further in different sectors such as modern methods of construction, specific volumetric or panelized modular construction, or 3D printing for achieving sustainable development goals (SDGs). In line with SDGs, the authors will continue this study to explore applications of mixed reality along with BIM for risk identification in construction.

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References

1. Davila Delgado, J.M.; Oyedele, L.; Beach, T.; Demian, P. Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption. *J. Constr. Eng. Manag.* **2020**, *146*, 1–17. [CrossRef]
2. ISO 19650-1:2018 ISO 19650-1:2018(en). *Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)—Information Management Using Building Information Modelling—Part 1: Concepts and Principles*; ISO: Geneva, Switzerland, 2018.
3. Waterhouse, R. 10th Annual BIM Report, National Building Specification. NBS UK, 2020.
4. Hu, H. Development of Interoperable Data Protocol for Integrated Bridge Project Delivery. Ph.D. Thesis, State University of New York, Buffalo, NY, USA, 2014.
5. Shirole, A.M.; Riordan, T.J.; Chen, S.S.; Gao, Q.; Hu, H.; Puckett, J.A. BrIM for project delivery and the life-cycle: State of the art. *Bridg. Struct.* **2009**, *5*, 173–187. [CrossRef]
6. Alizadehsalehi, S.; Hadavi, A.; Huang, J.C. From BIM to extended reality in AEC industry. *Autom. Constr.* **2020**, *116*, 103254. [CrossRef]
7. Zhang, Y.; Liu, H.; Kang, S.; Al-hussein, M. Automation in Construction Virtual reality applications for the built environment: Research trends and opportunities. *Autom. Constr.* **2020**, *118*, 103311. [CrossRef]
8. Abbas, A.; Choi, M.; Seo, J.; Cha, S.H.; Li, H. Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects. *KSCE J. Civ. Eng.* **2019**, *23*, 4972–4983. [CrossRef]
9. Suh, A.; Prophet, J. The state of immersive technology research: A literature analysis. *Comput. Human Behav.* **2018**, *86*, 77–90. [CrossRef]
10. Cipresso, P.; Giglioli, I.A.C.; Raya, M.A.; Riva, G. The past, present, and future of virtual and augmented reality research: A network and cluster analysis of the literature. *Front. Psychol.* **2018**, *9*, 1–20. [CrossRef] [PubMed]
11. Li, R.Y.M. *Virtual Reality and Construction Safety BT—An Economic Analysis on Automated Construction Safety: Internet of Things, Artificial Intelligence and 3D Printing*; Li, R.Y.M., Ed.; Springer: Singapore, 2018; pp. 117–136.
12. Muhammad, A.A.; Yitmen, I.; Alizadehsalehi, S.; Celik, T. Adoption of Virtual Reality (VR) for Site Layout Optimization of Construction Projects. *Tek. Dergi* **2020**, 9833–9850. [CrossRef]
13. Leue, M.; tom Dieck, D.; Jung, T. *A Theoretical Model of Augmented Reality Acceptance*; E-review of Tourism Research; Texas A & M University: College Station, TX, USA, 2014; Volume 5.
14. Son, H.; Lee, S.; Hwang, N.; Kim, C. The adoption of building information modeling in the design organization: An empirical study of architects in Korean design firms. In Proceedings of the 31st International Symposium on Automation and Robotics in Construction and Mining—ISARC 2014, Sydney, Australia, 9–11 July 2014; pp. 194–201.
15. tom Dieck, M.C.; Jung, T. A theoretical model of mobile augmented reality acceptance in urban heritage tourism. *Curr. Issues Tour.* **2018**, *21*, 154–174. [CrossRef]
16. Lee, S.; Yu, J. Comparative Study of BIM Acceptance between Korea and the United States. *J. Constr. Eng. Manag.* **2016**, *142*, 1–9. [CrossRef]
17. Piroozfar, A.; Farr, E.R.P.; Boseley, S.; Essa, A.; Jin, R. The application of Augmented Reality (AR) in the Architecture Engineering and Construction (AEC) industry. In Proceedings of the Tenth International Conference on Construction in the 21st Century, Colombo, Sri Lanka, 2–4 July 2018.
18. Naticchia, B.; Corneli, A.; Carbonari, A.; Bonci, A.; Pirani, M. Mixed reality approach for the management of building maintenance and operation. In Proceedings of the ISARC 2018—35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things, Berlin, Germany, 20–25 July 2018.
19. El Ammari, K.; Hammad, A. Remote interactive collaboration in facilities management using BIM-based mixed reality. *Autom. Constr.* **2019**, *107*, 102940. [CrossRef]
20. Sepasgozar, S.M.E. Digital twin and web-based virtual gaming technologies for online education: A case of construction management and engineering. *Appl. Sci.* **2020**, *10*, 4678. [CrossRef]
21. Protchenko, K.; Dlbrowski, P.; Garbacz, A. Development and Assessment of VR/AR Solution for Verification during the Construction Process. *MATEC Web Conf.* **2018**, *196*, 04083. [CrossRef]
22. Orihuela, P.; Noel, M.; Pacheco, S.; Orihuela, J.; Yaya, C.; Aguilar, R. Application of virtual and augmented reality techniques during design and construction process of building projects. 27th Annual Conference of the International Group for Lean Construction IGLC; IGLC: Dublin, Ireland, 3–5 July 2019; pp. 1105–1116.

23. Perrier, N.; Bled, A.; Bourgault, M.; Cousin, N.; Danjou, C.; Pellerin, R.; Roland, T. Construction 4.0: A survey of research trends. *J. Inf. Technol. Constr.* **2020**, *25*, 416–437. [CrossRef]
24. Pour Rahimian, F.; Seyedzadeh, S.; Oliver, S.; Rodriguez, S.; Dawood, N. On-demand monitoring of construction projects through a game-like hybrid application of BIM and machine learning. *Autom. Constr.* **2020**, *110*, 103012. [CrossRef]
25. International Data Corporation. *Worldwide Quarterly Augmented and Virtual Reality Headset Tracker-Second Quarter*; International Data Corporation: Framingham, MA, USA, 2017.
26. Forcael, E.; Ferrari, I.; Opazo-Vega, A.; Pulido-Arcas, J.A. Construction 4.0: A literature review. *Sustainability* **2020**, *12*, 9755. [CrossRef]
27. Rose-Ackerman, S. Introduction and overview. *Int. Handb. Econ. Corrupt.* **2006**, 3–22. [CrossRef]
28. Hou, L.; Wu, S.; Zhang, G.K.; Tan, Y.; Wang, X. Literature review of digital twins applications in constructionworkforce safety. *Appl. Sci.* **2021**, *11*, 339. [CrossRef]
29. Boje, C.; Guerriero, A.; Kubicki, S.; Rezgui, Y. Towards a semantic Construction Digital Twin: Directions for future research. *Autom. Constr.* **2020**, *114*, 103179. [CrossRef]
30. Gerber, D.; Nguyen, B.; Gaetani, I. *Digital Twin: Towards a Meaningful Framework*; Arup: New York, NY, USA, 2019; p. 160.
31. Pavón, R.M.; Arcos Alvarez, A.A.; Alberti, M.G. Possibilities of BIM-FM for the Management of COVID in Public Buildings. *Sustainability* **2020**, *12*, 9974. [CrossRef]
32. Palmarini, R.; Erkoyuncu, J.A.; Roy, R.; Torabmostaedi, H. A systematic review of augmented reality applications in maintenance. *Robot. Comput. Integr. Manuf.* **2018**, *49*, 215–228. [CrossRef]
33. Glegg, S.M.N.; Levac, D.E. Barriers, Facilitators and Interventions to Support Virtual Reality Implementation in Rehabilitation: A Scoping Review. *PM R* **2018**, *10*, 1237–1251.e1. [CrossRef] [PubMed]
34. Manyika, J.; Ramaswamy, S.; Khanna, S.; Sarrazin, H.; Pinkus, G.; Sethupathy, G.; Yaffe, A. *Executive Summary Digital America: A Tale of the Haves and Have-Mores*; McKinsey&Company: New York, NY, USA, 2015.
35. Rauschnabel, P.A.; Rossmann, A.; tom Dieck, M.C. An adoption framework for mobile augmented reality games: The case of Pokémon Go. *Comput. Human Behav.* **2017**, *76*, 276–286. [CrossRef]
36. Cheng, J.C.P.; Chen, K.; Chen, W. State-of-the-Art Review on Mixed Reality Applications in the AECO Industry. *J. Constr. Eng. Manag.* **2020**, *146*, 1–12. [CrossRef]
37. Diao, P.H.; Shih, N.J. Trends and research issues of augmented reality studies in architectural and civil engineering education-A review of academic journal publications. *Appl. Sci.* **2019**, *9*, 1840. [CrossRef]
38. Chuah, S.H.-W. Why and Who Will Adopt Extended Reality Technology? Literature Review, Synthesis, and Future Research Agenda. *SSRN Electron. J.* **2019**. [CrossRef]
39. Motawa, I.; Almarshad, A. A knowledge-based BIM system for building maintenance. *Autom. Constr.* **2013**, *29*, 173–182. [CrossRef]
40. Becerik-Gerber, B.; Jazizadeh, F.; Li, N.; Calis, G. Application areas and data requirements for BIM-enabled facilities management. *J. Constr. Eng. Manag.* **2012**, *138*, 431–442. [CrossRef]
41. Li, X.; Yi, W.; Chi, H.L.; Wang, X.; Chan, A.P.C. A critical review of virtual and augmented reality (VR/AR) applications in construction safety. *Autom. Constr.* **2018**, *86*, 150–162. [CrossRef]
42. Wang, J.; Wang, X.; Shou, W.; Xu, B. Integrating BIM and augmented reality for interactive architectural visualisation. *Constr. Innov.* **2014**, *14*, 453–476. [CrossRef]
43. Milgram, P.; Takemura, H.; Utsumi, A.; Kishino, F. Augmented reality: A class of displays on the reality-virtuality continuum. *Telemanipulator Telepresence Technol.* **1995**, *2351*, 282–292.
44. Zhang, C.; Perkis, A.; Arndt, S. Spatial immersion versus emotional immersion, which is more immersive? In Proceedings of the 2017 9th International Conference on Quality of Multimedia Experience QoMEX 2017, Erfurt, Germany, 31 May–2 June 2017.
45. Asgari, Z.; Rahimian, F.P. Advanced Virtual Reality Applications and Intelligent Agents for Construction Process Optimisation and Defect Prevention. *Procedia Eng.* **2017**, *196*, 1130–1137. [CrossRef]
46. Boga, S.R.C.; Kansagara, B.; Kannan, R. Integration of Augmented Reality and Virtual Reality in building information modeling: The next frontier in civil engineering education. *Virtual Augment. Real. Concepts Methodol. Tools Appl.* **2018**, *2*, 1037–1066.
47. Kim, M.J.; Wang, X.; Love, P.E.D.; Li, H.; Kang, S.C. Virtual reality for the built environment: A critical review of recent advances. *J. Inf. Technol. Constr.* **2013**, *18*, 279–305.
48. Whyte, J. Industrial Applications of Virtual Reality in architecture and construction. *J. Inf. Technol. Constr. (ITcon)* **2003**, *8*, 43–50.
49. Heydarian, A.; Carneiro, J.P.; Gerber, D.; Becerik-Gerber, B.; Hayes, T.; Wood, W. Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations. *Autom. Constr.* **2015**, *54*, 116–126. [CrossRef]
50. Hinckley, K.; Pausch, R.; Goblel, J.C.; Kassell, N.F. A survey of design issues in spatial input. In Proceedings of the 7th ACM Symposium on User Interface and Software Technology UIST 1994, Marina del Rey, CA, USA, 2–4 November 1994; pp. 213–222.
51. Wang, X.; Love, P.E.D.; Kim, M.J.; Wang, W. Mutual awareness in collaborative design: An Augmented Reality integrated telepresence system. *Comput. Ind.* **2014**, *65*, 314–324. [CrossRef]

52. Tariq, M.A.; Farooq, U.; Aamir, E.; Shafaqat, R. Exploring Adoption of Integrated Building Information Modelling and Virtual Reality. In Proceedings of the 1st International Conference on Electrical, Communication, and Computer Engineering ICECCE 2019, Swat, Pakistan, 24–25 July 2019; pp. 1–6.
53. Zaker, R.; Coloma, E. Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: A case study. *Vis. Eng.* **2018**, *6*. [CrossRef]
54. Anumba, C.J.; Pan, J.; Issa, R.R.A.; Mutis, I. Collaborative project information management in a semantic web environment. *Eng. Constr. Archit. Manag.* **2008**, *15*, 78–94. [CrossRef]
55. Aral, S.; Brynjolfsson, E.; Van Alstyne, M. Information, technology, and information worker productivity. *Inf. Syst. Res.* **2012**, *23*, 849–867. [CrossRef]
56. Hou, L.; Wang, X.; Bernold, L.; Love, P.E.D. Using animated augmented reality to cognitively guide assembly. *J. Comput. Civ. Eng.* **2013**, *27*, 439–451. [CrossRef]
57. Meža, S.; Turk, Ž.; Dolenc, M. Component based engineering of a mobile BIM-based augmented reality system. *Autom. Constr.* **2014**, *42*, 1–12. [CrossRef]
58. Caudell, T.P.; Mizell, D.W. Augmented reality: An application of heads-up display technology to manual manufacturing processes. In Proceedings of the Hawaii International Conference on System Sciences, Kauai, HI, USA, 7–10 January 2003; Volume 2, pp. 659–669.
59. Azuma, R.; Baillot, Y.; Behringer, R.; Feiner, S.; Julier, S.; MacIntyre, B. Recent advances in augmented reality. *IEEE Comput. Graph. Appl.* **2001**, *21*, 34–47. [CrossRef]
60. Chi, H.L.; Kang, S.C.; Wang, X. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Autom. Constr.* **2013**, *33*, 116–122. [CrossRef]
61. Jiao, Y.; Zhang, S.; Li, Y.; Wang, Y.; Yang, B. Towards cloud Augmented Reality for construction application by BIM and SNS integration. *Autom. Constr.* **2013**, *33*, 37–47. [CrossRef]
62. Billinghurst, M.; Clark, A.; Lee, G. A survey of augmented reality. *Found. Trends Human Comput. Interact.* **2014**, *8*, 73–272. [CrossRef]
63. Carmigniani, J.; Furht, B.; Anisetti, M.; Ceravolo, P.; Damiani, E.; Ivkovic, M. Augmented reality technologies, systems and applications. *Multimed. Tools Appl.* **2011**, *51*, 341–377. [CrossRef]
64. Feiner, S.; Maclntyre, B.; Webster, A. A Touring Hachine: Prototgping 3D Hobite Augmented Reatitg Sgstems for Exptoring the Urban Environment. *Pers. Technol.* **1997**, *1*, 208–217. [CrossRef]
65. Milgram, P.; Kishino, F. A taxonomy of mixed reality visual displays. *IEICE Trans. Inf. Syst.* **1994**, *E77–D*, 1–15.
66. Milgram, P.; Colquhoun, H. A Taxonomy of Real and Virtual World Display Integration. *Mix. Real.* **1999**, 5–30.
67. Dunston, P.S.; Wang, X. An iterative methodology for mapping mixed reality technologies to AEC operations. *Electron. J. Inf. Technol. Constr.* **2011**, *16*, 509–528.
68. Wang, X.; Dunston, P.S. Comparative Effectiveness of Mixed Reality-Based Virtual Environments in Collaborative Design. *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.* **2011**, *41*, 284–296. [CrossRef]
69. Vision Network Report, Centre for Digital Built Britain. University of Cambridge: Cambridge, UK, 20 December 2018.
70. Wang, X.; Dunston, P.S. Compatibility issues in Augmented Reality systems for AEC: An experimental prototype study. *Autom. Constr.* **2006**, *15*, 314–326. [CrossRef]
71. Zabidin, N.S.; Belayutham, S.; Ibrahim, C.K.I.C. A bibliometric and scientometric mapping of Industry 4.0 in construction. *J. Inf. Technol. Constr.* **2020**, *25*, 287–307.
72. Bishop, G.; Fuchs, H. Research directions in virtual environments. *ACM SIGGRAPH Comput. Graph.* **1992**, *26*, 153–177. [CrossRef]
73. Gigante, M.A. 1—Virtual Reality: Definitions, History and Applications. In *Virtual Reality Systems*; Earnshaw, R.A., Gigante, M.A., Jones, H.B.T.-V.R.S., Eds.; Academic Press: Boston, MA, USA, 1993; pp. 3–14. ISBN 978-0-12-227748-1.
74. Cruz-Neira, C.; Leigh, J.; Papka, M.; Barnes, C.; Cohen, S.M.; Das, S.; Engelmann, R.; Hudson, R.; Roy, T.; Siegel, L.; et al. Scientists in wonderland: A report on visualization applications in the CAVE virtual reality environment. In Proceedings of the 1993 IEEE Research Properties in Virtual Reality Symposium VRAIS 1993, San Jose, CA, USA, 25–26 October 1993; pp. 59–66.
75. Warwick, K.; Gray, J.; Roberts, D. *Virtual Reality in Engineering*; Institution of Electrical Engineers: London, UK, 1993.
76. Diemer, J.; Alpers, G.W.; Peperkorn, H.M.; Shiban, Y.; Mühlberger, A. The impact of perception and presence on emotional reactions: A review of research in virtual reality. *Front. Psychol.* **2015**, *6*, 1–9. [CrossRef] [PubMed]
77. Yim, M.Y.C.; Chu, S.C.; Sauer, P.L. Is Augmented Reality Technology an Effective Tool for E-commerce? An Interactivity and Vividness Perspective. *J. Interact. Mark.* **2017**, *39*, 89–103. [CrossRef]
78. Tussyadiah, I.P. Virtual Reality, Presence, and Attitude Change: Empirical Evidence from Tourism. Ph.D. Thesis, Guildford, UK, 2017.
79. Slater, M.; Sanchez-Vives, M.V. Enhancing our lives with immersive virtual reality. *Front. Robot. AI* **2016**, *3*, 1–47. [CrossRef]
80. Skalski, P.; Tamborini, R. The role of social presence in interactive agent-based persuasion. *Media Psychol.* **2007**, *10*, 385–413. [CrossRef]
81. Fluke, C.J.; Barnes, D.G. The Ultimate Display. Cornell University: Ithca, NY, USA, 2016; pp. 4–5. Available online: https://arxiv.org/abs/1601.03459 (accessed on 10 January 2021).

82. Guo, H.L.; Li, H.; Li, V. VP-based safety management in large-scale construction projects: A conceptual framework. *Autom. Constr.* **2013**, *34*, 16–24. [CrossRef]
83. Steuer, J. Defining virtual reality: Characteristics determining telepresence. *J. Commun.* **1992**, *42*, 73–94. [CrossRef]
84. Wang, B.; Li, H.; Rezgui, Y.; Bradley, A.; Ong, H.N. BIM based virtual environment for fire emergency evacuation. *Sci. World J.* **2014**, *2014*. [CrossRef] [PubMed]
85. Kuncham, K. Timelining The Construction in Immersive Virtual Reality System Using BIM Application. Master's Thesis, Texas A & M University, College Station, TX, USA, 2013.
86. Dunston, P.S.; Arns, L.L.; McGlothlin, J.D. Virtual reality mock-ups for healthcare facility design and a model for technology hub collaboration. *J. Build. Perform. Simul.* **2010**, *3*, 185–195. [CrossRef]
87. Svalestuen, F.; Knotten, V.; Lædre, O.; Drevland, F.; Lohne, J. Using Building Information Model (Bim) Devices To Improve Information Flow and Collaboration on Construction Sites. *J. Inf. Technol. Constr.* **2017**, *22*, 204–219.
88. Jensen, C.G. Collaboration and Dialogue in Virtual Reality. *Collab. Dialogue Virtual Real.* **2017**, *5*, 85–110.
89. Romano, S.; Capece, N.; Erra, U.; Scanniello, G.; Lanza, M. On the use of virtual reality in software visualization: The case of the city metaphor. *Inf. Softw. Technol.* **2019**, *114*, 92–106. [CrossRef]
90. Virtual, U.; Interface, R.; Sherman, W.R.; Craig, A.B.; Varshney, A.; Watson, B. *Reviews Level of Detail for 3D Graphics*; Morgan Kaufmann Publishers Inc.: San Francisco, CA, USA, 1993; pp. 441–442.
91. Sampaio, A.Z.; Martins, O.P. The application of virtual reality technology in the construction of bridge: The cantilever and incremental launching methods. *Autom. Constr.* **2014**, *37*, 58–67. [CrossRef]
92. Du, J.; Zou, Z.; Shi, Y.; Zhao, D. Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making. *Autom. Constr.* **2018**, *85*, 51–64. [CrossRef]
93. Zhao, D.; Lucas, J. Virtual reality simulation for construction safety promotion. *Int. J. Inj. Contr. Saf. Promot.* **2015**, *22*, 57–67. [CrossRef]
94. Boud, A.C.; Haniff, D.J.; Baber, C.; Steiner, S.J. Virtual reality and augmented reality as a training tool for assembly tasks. In Proceedings of the 1999 IEEE International Conference on Information Visualization (Cat. No. PR00210), London, UK, 14–16 July 1999; pp. 32–36.
95. Fogarty, J.; McCormick, J.; El-Tawil, S. Improving Student Understanding of Complex Spatial Arrangements with Virtual Reality. *J. Prof. Issues Eng. Educ. Pract.* **2018**, *144*, 1–10. [CrossRef]
96. Paes, D.; Arantes, E.; Irizarry, J. Immersive environment for improving the understanding of architectural 3D models: Comparing user spatial perception between immersive and traditional virtual reality systems. *Autom. Constr.* **2017**, *84*, 292–303. [CrossRef]
97. Ventura, S.M.; Castronovo, F.; Ciribini, A.L.C. A design review session protocol for the implementation of immersive virtual reality in usability-focused analysis. *J. Inf. Technol. Constr.* **2020**, *25*, 233–253.
98. Aromaa, S.; Väänänen, K. Suitability of virtual prototypes to support human factors/ergonomics evaluation during the design. *Appl. Ergon.* **2016**, *56*, 11–18. [CrossRef]
99. Berg, L.P.; Vance, J.M. An Industry Case Study: Investigating Early Design Decision Making in Virtual Reality. *J. Comput. Inf. Sci. Eng.* **2016**, *17*. [CrossRef]
100. Ozacar, K.; Ortakci, Y.; Kahraman, I.; Durgut, R.; Karas, I.R. A low-cost and lightweight 3D interactive real estate-purposed indoor virtual reality applicatioN. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *4*, 307–310. [CrossRef]
101. Froehlich, M.; Azhar, S. Investigating virtual reality headset applications in construction. In Proceedings of the 52nd ASC, Provo, UT, USA, 13–16 April 2016.
102. Azuma, R.T. A Survey of Augmented Reality. *Presence Teleoperators Virtual Environ.* **1997**, *6*, 355–385. [CrossRef]
103. Behzadan, A.H.; Kamat, V.R. Visualization of construction graphics in outdoor augmented reality. In Proceedings of the Winter Simulation Conference, Orlando, FL, USA, 4 December 2005; pp. 1914–1920.
104. Wang, X.; Love, P.E.D.; Kim, M.J.; Park, C.S.; Sing, C.P.; Hou, L. A conceptual framework for integrating building information modeling with augmented reality. *Autom. Constr.* **2013**, *34*, 37–44. [CrossRef]
105. Chu, M.; Matthews, J.; Love, P.E.D. Integrating mobile Building Information Modelling and Augmented Reality systems: An experimental study. *Autom. Constr.* **2018**, *85*, 305–316. [CrossRef]
106. Behzadan, A.H.; Kamat, V.R. Enabling discovery-based learning in construction using telepresent augmented reality. *Autom. Constr.* **2013**, *33*, 3–10. [CrossRef]
107. Behzadan, A.H.; Kamat, V.R. Georeferenced registration of construction graphics in mobile outdoor augmented reality. *J. Comput. Civ. Eng.* **2007**, *21*, 247–258. [CrossRef]
108. Shirazi, A.; Behzadan, A.H. Design and assessment of a mobile augmented reality-based information delivery tool for construction and civil engineering curriculum. *J. Prof. Issues Eng. Educ. Pract.* **2015**, *141*, 1–10. [CrossRef]
109. Shin, D.H.; Dunston, P.S. Identification of application areas for Augmented Reality in industrial construction based on technology suitability. *Autom. Constr.* **2008**, *17*, 882–894. [CrossRef]
110. Shin, D.H.; Dunston, P.S. Technology development needs for advancing Augmented Reality-based inspection. *Autom. Constr.* **2010**, *19*, 169–182. [CrossRef]
111. Ganiev, A.; Shin, H.S.; Lee, K.H. Implementation of online and offline Building Information System based on Virtual Reality and Augmented Reality. *Int. J. Eng. Technol.* **2018**, *7*, 37–40. [CrossRef]

112. Behzadan, A.H.; Timm, B.W.; Kamat, V.R. General-purpose modular hardware and software framework for mobile outdoor augmented reality applications in engineering. *Adv. Eng. Inform.* **2008**, *22*, 90–105. [CrossRef]
113. Chalhoub, J.; Ayer, S.K. Effect of varying task attributes on augmented reality aided point layout. *J. Inf. Technol. Constr.* **2019**, *24*, 95–111.
114. Behzadan, A.H.; Kamat, V.R. Interactive augmented reality visualization for improved damage prevention and maintenance of underground infrastructure. In Proceedings of the Construction Research Congress 2009: Building a Sustainable Future, Seattle, WA, USA, 5–7 April 2009; pp. 1214–1222.
115. Agrawal, A.; Acharya, G.; Balasubramanian, K.; Agrawal, N.; Chaturvedi, R. A Review on the use of Augmented Reality to Generate Safety Awareness and Enhance Emergency Response. *Int. J. Curr. Eng. Technol.* **2016**, *6*, 813–820.
116. Grubert, J.; Langlotz, T.; Zollmann, S.; Regenbrecht, H. Towards pervasive augmented reality: Context-awareness in augmented reality. *IEEE Trans. Vis. Comput. Graph.* **2017**, *23*, 1706–1724. [CrossRef]
117. Mani, G.F.; Feniosky, P.M.; Savarese, S. D4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication. *Electron. J. Inf. Technol. Constr.* **2009**, *14*, 129–153.
118. Golparvar-Fard, M.; Peña-Mora, F.; Savarese, S. Integrated sequential as-built and as-planned representation with D 4AR tools in support of decision-making tasks in the AEC/FM industry. *J. Constr. Eng. Manag.* **2011**, *137*, 1099–1116. [CrossRef]
119. Park, C.S.; Lee, D.Y.; Kwon, O.S.; Wang, X. A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template. *Autom. Constr.* **2013**, *33*, 61–71. [CrossRef]
120. Park, C.-S.; Kim, H.-J. A framework for construction safety management and visualization system. *Autom. Constr.* **2013**, *33*, 95–103. [CrossRef]
121. Wang, X.; Kim, M.J.; Love, P.E.D.; Kang, S.C. Augmented reality in built environment: Classification and implications for future research. *Autom. Constr.* **2013**, *32*, 1–13. [CrossRef]
122. Hsieh, S.H.; Kang, S.C.; Ting-Hui, L.I.N. Augmented reality system and method for on-site construction process. U.S. Patent No 9,436,427, 6 September 2016.
123. Bae, H.; Golparvar-Fard, M.; White, J. High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications. *Vis. Eng.* **2013**, *1*, 1–13. [CrossRef]
124. Yeh, K.C.; Tsai, M.H.; Kang, S.C. On-site building information retrieval by using projection-based augmented reality. *J. Comput. Civ. Eng.* **2012**, *26*, 342–355. [CrossRef]
125. Hou, L.; Wang, X.; Truijens, M. Using augmented reality to facilitate piping assembly: An experiment-based evaluation. *J. Comput. Civ. Eng.* **2015**, *29*, 1–12. [CrossRef]
126. Kwon, O.S.; Park, C.S.; Lim, C.R. A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality. *Autom. Constr.* **2014**, *46*, 74–81. [CrossRef]
127. Wang, X.; Love, P.E.D. BIM + AR: Onsite information sharing and communication via advanced visualization. In Proceedings of the 2012 IEEE 16th International Conference on Computer Supported Cooperative Work in Design CSCWD 2012, Wuhan, China, 23–25 May 2012; pp. 850–855.
128. Rankohi, S.; Waugh, L. Review and analysis of augmented reality literature for construction industry. *Vis. Eng.* **2013**, *1*, 1–18. [CrossRef]
129. Lee, J.; Kim, J.; Ahn, J.; Woo, W. Context-aware risk management for architectural heritage using historic building information modeling and virtual reality. *J. Cult. Herit.* **2019**, *38*, 242–252. [CrossRef]
130. Holz, T.; Campbell, A.G.; O'Hare, G.M.P.; Stafford, J.W.; Martin, A.; Dragone, M. MiRA—Mixed Reality Agents. *Int. J. Hum. Comput. Stud.* **2011**, *69*, 251–268. [CrossRef]
131. Ohta, Y.; Tamura, H. *Mixed Reality: Merging Real and Virtual Worlds*; Springer Publishing Company: Berlin/Heidelberg, Germany, 2014; ISBN 3642875149.
132. Dai, F.; Olorunfemi, A.; Peng, W.; Cao, D.; Luo, X. Can mixed reality enhance safety communication on construction sites? An industry perspective. *Saf. Sci.* **2021**, *133*, 105009. [CrossRef]
133. Arroyo, E.; Righi, V.; Blat, J.; Ardaiz, O. Distributed multi-touch virtual collaborative environments. In Proceedings of the 2010 International Symposium on Collaborative Technologies and Systems, Chicago, IL, USA, 17–21 May 2010; pp. 635–636.
134. Hauber, J.; Regenbrecht, H.; Billinghurst, M.; Cockburn, A. Spatiality in videoconferencing: Trade-offs between efficiency and social presence. In Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work, Banff, AB, Canada, 4–8 November 2006; pp. 413–422.
135. Brito, C.; Alves, N.; Magalhães, L.; Guevara, M. Bim mixed reality tool for the inspection of heritage buildings. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2019**, *4*, 25–29. [CrossRef]
136. El Ammari, K.; Hammad, A. Collaborative BIM-based markerless mixed reality framework for facilities maintenance. In Proceedings of the International Conference on Computing in Civil and Building Engineering, Orlando, FL, USA, 23–25 June 2014; pp. 657–664.
137. Kim, T.; Jeong, J.; Kim, Y.; Gu, H.; Woo, S.; Choo, S. A basic study on methodology of maintenance management using MR. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction ISARC 2019, Banff, AB, Canada, 21–24 May 2019; pp. 360–367.

138. Dunston, P.S.; Wang, X. Mixed Reality-based visualization interfaces for architecture, engineering, and construction industry. *J. Constr. Eng. Manag.* **2005**, *131*, 1301–1309. [CrossRef]
139. Saratu, T.; Chimay, A.; Somayeh, A. Construction Research Congress. In *BIM Implementation in Facilities Management: An Analysis of Implementation Processes*; American Society of Civil Engineers: Reston, VA, USA, 2018; pp. 725–735.
140. Alizadehsalehi, S.; Hadavi, A. BIM/MR-Lean Construction Project Delivery Management System. In Proceedings of the 2019 IEEE Technology & Engineering Management Conference (TEMSCON), Atlanta, GA, USA, 12–14 June 2019; pp. 1–6.
141. Riexinger, G.; Kluth, A.; Olbrich, M.; Braun, J.D.; Bauernhansl, T. Mixed Reality for On-Site Self-Instruction and Self-Inspection with Building Information Models. *Procedia CIRP* **2018**, *72*, 1124–1129. [CrossRef]
142. Wang, X.; Dunston, P.S. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. *Autom. Constr.* **2008**, *17*, 399–412. [CrossRef]
143. Sheng, Y.; Yapo, T.C.; Young, C.; Cutler, B. A Spatially Augmented Reality Sketching Interface for Architectural Daylighting Design. *IEEE Trans. Vis. Comput. Graph.* **2011**, *17*, 38–50. [CrossRef] [PubMed]
144. Ge, L.; Kuester, F. Integrative simulation environment for conceptual structural analysis. *J. Comput. Civ. Eng.* **2015**, *29*, 1–10. [CrossRef]
145. Turkan, Y.; Radkowski, R.; Karabulut-Ilgu, A.; Behzadan, A.H.; Chen, A. Mobile augmented reality for teaching structural analysis. *Adv. Eng. Inform.* **2017**, *34*, 90–100. [CrossRef]
146. Ayer, S.K.; Messner, J.I.; Anumba, C.J. Development of ecocampus: A prototype system for sustainable building design education. *J. Inf. Technol. Constr.* **2014**, *19*, 520–533.
147. Fiorentino, M.; Uva, A.E.; Monno, G.; Radkowski, R. Augmented Technical Drawings: A Novel Technique for Natural Interactive Visualization of Computer-Aided Design Models. *J. Comput. Inf. Sci. Eng.* **2012**, *12*. [CrossRef]
148. Bae, H.; Golparvar-Fard, M.; White, J. Image-based localization and content authoring in structure-from-motion point cloud models for real-time field reporting applications. *J. Comput. Civ. Eng.* **2015**, *29*, 1–13. [CrossRef]
149. Yang, M.-D.; Chao, C.-F.; Huang, K.-S.; Lu, L.-Y.; Chen, Y.-P. Image-based 3D scene reconstruction and exploration in augmented reality. *Autom. Constr.* **2013**, *33*, 48–60. [CrossRef]
150. Albert, A.; Hallowell, M.R.; Kleiner, B.; Chen, A.; Golparvar-Fard, M. Enhancing construction hazard recognition with high-fidelity augmented virtuality. *J. Constr. Eng. Manag.* **2014**, *140*, 1–11. [CrossRef]
151. Kim, H.S.; Kim, S.K.; Borrmann, A.; Kang, L.S. Improvement of Realism of 4D Objects Using Augmented Reality Objects and Actual Images of a Construction Site. *KSCE J. Civ. Eng.* **2018**, *22*, 2735–2746. [CrossRef]
152. Kim, C.; Park, T.; Lim, H.; Kim, H. On-site construction management using mobile computing technology. *Autom. Constr.* **2013**, *35*, 415–423. [CrossRef]
153. Bosché, F.; Abdel-Wahab, M.; Carozza, L. Towards a Mixed Reality System for Construction Trade Training. *J. Comput. Civ. Eng.* **2016**, *30*, 1–12. [CrossRef]
154. Lin, T.-J.; Duh, H.B.-L.; Li, N.; Wang, H.-Y.; Tsai, C.-C. An investigation of learners' collaborative knowledge construction performances and behavior patterns in an augmented reality simulation system. *Comput. Educ.* **2013**, *68*, 314–321. [CrossRef]
155. Chen, Y.C.; Chi, H.L.; Kang, S.C.; Hsieh, S.H. Attention-Based User Interface Design for a Tele-Operated Crane. *J. Comput. Civ. Eng.* **2016**, *30*, 1–12. [CrossRef]
156. Chi, H.-L.; Chen, Y.-C.; Kang, S.-C.; Hsieh, S.-H. Development of user interface for tele-operated cranes. *Adv. Eng. Inform.* **2012**, *26*, 641–652. [CrossRef]
157. Kim, B.; Kim, C.; Kim, H. Interactive modeler for construction equipment operation using augmented reality. *J. Comput. Civ. Eng.* **2012**, *26*, 331–341. [CrossRef]
158. Dai, F.; Dong, S.; Kamat, V.R.; Lu, M. Photogrammetry assisted measurement of interstory drift for rapid post-disaster building damage reconnaissance. *J. Nondestruct. Eval.* **2011**, *30*, 201–212. [CrossRef]
159. Dong, S.; Feng, C.; Kamat, V.R. Sensitivity analysis of augmented reality-assisted building damage reconnaissance using virtual prototyping. *Autom. Constr.* **2013**, *33*, 24–36. [CrossRef]
160. Kamat, V.R.; El-Tawil, S. Evaluation of augmented reality for rapid assessment of earthquake-induced building damage. *J. Comput. Civ. Eng.* **2007**, *21*, 303–310. [CrossRef]
161. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; Prisma Group. Reprint—Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Phys. Ther.* **2009**, *89*, 873–880. [CrossRef] [PubMed]
162. Shahruddin, S.; Zairul, M. BIM requirements across a construction project lifecycle: A PRISMA-compliant systematic review and meta-analysis. *Int. J. Innov. Creat. Chang.* **2020**, *12*, 569–590.
163. Sidani, A.; Dinis, F.M.; Sanhudo, L.; Duarte, J.; Santos Baptista, J.; Poças Martins, J.; Soeiro, A. Recent Tools and Techniques of BIM-Based Virtual Reality: A Systematic Review. *Arch. Comput. Methods Eng.* **2019**. [CrossRef]
164. Mansoori, S. Which is Better, a Conference Paper or Journal Publication? 2013. Available online: https://www.researchgate.net/post/Which_is_better_a_conference_paper_or_journal_publication (accessed on 7 February 2021).
165. Wen, J.; Gheisari, M. Using virtual reality to facilitate communication in the AEC domain: A systematic review. *Constr. Innov.* **2020**, *20*, 509–542. [CrossRef]
166. Aghaei Chadegani, A.; Salehi, H.; Md Yunus, M.M.; Farhadi, H.; Fooladi, M.; Farhadi, M.; Ale Ebrahim, N. A comparison between two main academic literature collections: Web of science and scopus databases. *Asian Soc. Sci.* **2013**, *9*, 18–26. [CrossRef]

167. van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
168. Sepasgozar, S.; Karimi, R.; Farahzadi, L.; Moezzi, F.; Shirowzhan, S.; Ebrahimzadeh, S.M.; Hui, F.; Aye, L. A Systematic Content Review of Artificial Intelligence and the Internet of Things Applications in Smart Home. *Appl. Sci.* **2020**, *10*, 3074. [CrossRef]
169. Xu, Y.; Zeng, J.; Chen, W.; Jin, R.; Li, B.; Pan, Z. A holistic review of cement composites reinforced with graphene oxide. *Constr. Build. Mater.* **2018**, *171*, 291–302. [CrossRef]
170. Cobo, M.J.; López-Herrera, A.G.; Herrera-Viedma, E.; Herrera, F. An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *J. Informetr.* **2011**, *5*, 146–166. [CrossRef]
171. Tijssen, R.J.W.; Van Raan, A.F.J. Mapping Changes in Science and Technology: Bibliometric Co-Occurrence Analysis of the R&D Literature. *Eval. Rev.* **1994**, *18*, 98–115.
172. Hammersley, M. On "systematic" reviews of research literatures: A "narrative" response to Evans & Benefield. *Br. Educ. Res. J.* **2001**, *27*, 543–554.
173. Bastian, M.; Heymann, S.; Jacomy, M. Gephi: An open source software for exploring and manipulating networks. In Proceedings of the International AAAI Conference on Weblogs and Social Media, San Jose, CA, USA, 17–20 May 2009; pp. 361–362.
174. Jin, R.; Zou, Y.; Gidado, K.; Ashton, P.; Painting, N. Scientometric analysis of BIM-based research in construction engineering and management. *Eng. Constr. Archit. Manag.* **2019**, *26*, 1750–1776. [CrossRef]
175. Martinez, P.; Al-Hussein, M.; Ahmad, R. A scientometric analysis and critical review of computer vision applications for construction. *Autom. Constr.* **2019**, *107*. [CrossRef]
176. Darko, A.; Chan, A.P.C.; Adabre, M.A.; Edwards, D.J.; Hosseini, M.R.; Ameyaw, E.E. Artificial intelligence in the AEC industry: Scientometric analysis and visualization of research activities. *Autom. Constr.* **2020**, *112*, 103081. [CrossRef]
177. Zhao, X. A scientometric review of global BIM research: Analysis and visualization. *Autom. Constr.* **2017**, *80*, 37–47. [CrossRef]
178. Ozturk, G.B. Interoperability in building information modeling for AECO/FM industry. *Autom. Constr.* **2020**, *113*, 103122. [CrossRef]
179. Hussein, M.; Zayed, T. Crane operations and planning in modular integrated construction: Mixed review of literature. *Autom. Constr.* **2021**, *122*, 103466. [CrossRef]
180. Wuni, I.Y.; Shen, G.Q.P.; Osei-Kyei, R. Scientometric review of global research trends on green buildings in construction journals from 1992 to 2018. *Energy Build.* **2019**, *190*, 69–85. [CrossRef]
181. Wang, P.; Wu, P.; Wang, J.; Chi, H.L.; Wang, X. A critical review of the use of virtual reality in construction engineering education and training. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1204. [CrossRef]
182. Marr, B. The Important Difference Between Virtual Reality, Augmented Reality and Mixed Reality. *Forbes Magazine*, 19 July 2019.
183. Rizzo, A.; Kim, G.J. A SWOT analysis of the field of virtual reality rehabilitation and therapy. *Presence Teleoperators Virtual Environ.* **2005**, *14*, 119–146. [CrossRef]
184. Juan, Y.K.; Chen, H.H.; Chi, H.Y. Developing and evaluating a virtual reality-based navigation system for pre-sale housing sales. *Appl. Sci.* **2018**, *8*, 952. [CrossRef]
185. Xia, S.A. Design and Implementation of Campus 3D Virtual Walkthrough System—Take Hunan Science and Technology University as an Example. *Appl. Mech. Mater.* **2013**, *268–270*, 1926–1929. [CrossRef]
186. Lin, Y.-C.; Chen, Y.-P.; Yien, H.-W.; Huang, C.-Y.; Su, Y.-C. Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital. *Adv. Eng. Inform.* **2018**, *36*, 130–145. [CrossRef]
187. Boton, C. Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation. *Autom. Constr.* **2018**, *96*, 1–15. [CrossRef]
188. Pejic, P.; Lakicevic, M.; Krasic, S.; Sidjanin, P. Application of Augmented and Virtual Reality in Residential Complex Presentation, Case Study: Energoprojekt Sunnyville. *J. Ind. Des. Eng. Graph.* **2017**, *12*, 127–133.
189. Nee, A.Y.C.; Ong, S.K.; Chryssolouris, G.; Mourtzis, D. Augmented reality applications in design and manufacturing. *CIRP Ann.* **2012**, *61*, 657–679. [CrossRef]
190. Eiris, R.; Gheisari, M. Research trends of virtual human applications in architecture, engineering and construction. *J. Inf. Technol. Constr.* **2017**, *22*, 168–184.
191. Lin, J.-R.; Cao, J.; Zhang, J.-P.; van Treeck, C.; Frisch, J. Visualization of indoor thermal environment on mobile devices based on augmented reality and computational fluid dynamics. *Autom. Constr.* **2019**, *103*, 26–40. [CrossRef]
192. Fukuda, T.; Yokoi, K.; Yabuki, N.; Motamedi, A. An indoor thermal environment design system for renovation using augmented reality. *J. Comput. Des. Eng.* **2019**, *6*, 179–188. [CrossRef]
193. Pour Rahimian, F.; Chavdarova, V.; Oliver, S.; Chamo, F.; Potseluyko Amobi, L. OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing. *Autom. Constr.* **2019**, *102*, 1–16. [CrossRef]
194. Graham, K.; Chow, L.; Fai, S. From BIM to VR: Defining a level of detail to guide virtual reality narratives. *J. Inf. Technol. Constr.* **2019**, *24*, 553–568. [CrossRef]
195. Dunston, P.S.; Arns, L.L.; Mcglothlin, J.D.; Lasker, G.C.; Kushner, A.G. An Immersive Virtual Reality Mock-Up for Design Review of Hospital Patient Rooms. In *Collaborative Design in Virtual Environments*; Wang, X., Tsai, J.J.-H., Eds.; Springer: Dordrecht, The Netherlands, 2011; pp. 167–176. ISBN 978-94-007-0605-7.
196. Williams, G.; Gheisari, M.; Chen, P.J.; Irizarry, J. BIM2MAR: An efficient BIM translation to mobile augmented reality applications. *J. Manag. Eng.* **2014**, *31*, 1–8. [CrossRef]

197. Dris, A.-S.; Lehericey, F.; Gouranton, V.; Arnaldi, B. OpenBIM Based IVE Ontology: An Ontological Approach to Improve Interoperability for Virtual Reality Applications. In *Advances in Informatics and Computing in Civil and Construction Engineering*; Mutis, I., Hartmann, T., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 129–136.
198. Dermott, M. Robots and AR: Towards a platform economy for construction. *J. Inf. Technol. Constr.* **2019**, *24*, 527–539. [CrossRef]
199. Ergun, O.; Akln, S.; Dino, I.G.; Surer, E. Architectural design in virtual reality and mixed reality environments: A comparative analysis. In Proceedings of the 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), Osaka, Japan, 23–27 March 2019; pp. 914–915.
200. Turner, C.J.; Hutabarat, W.; Oyekan, J.; Tiwari, A. Discrete Event Simulation and Virtual Reality Use in Industry: New Opportunities and Future Trends. *IEEE Trans. Human Mach. Syst.* **2016**, *46*, 882–894. [CrossRef]
201. Davidson, J.; Fowler, J.; Pantazis, C.; Sannino, M.; Walker, J.; Sheikhkhoshkar, M.; Rahimian, F.P. Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: A proof of concept study. *Front. Eng. Manag.* **2020**, *7*, 396–403. [CrossRef]
202. Zollmann, S.; Hoppe, C.; Kluckner, S.; Poglitsch, C.; Bischof, H.; Reitmayr, G. Augmented reality for construction site monitoring and documentation. *Proc. IEEE* **2014**, *102*, 137–154. [CrossRef]
203. Zhou, Y.; Luo, H.; Yang, Y. Implementation of augmented reality for segment displacement inspection during tunneling construction. *Autom. Constr.* **2017**, *82*, 112–121. [CrossRef]
204. Zaher, M.; Greenwood, D.; Marzouk, M. Mobile augmented reality applications for construction projects. *Constr. Innov.* **2018**, *18*, 152–166. [CrossRef]
205. Hsieh, S.-H. A Smart Crane Operations Assistance System Using Augmented Reality Technology. In Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC 2011), Seoul, Korea, 29 June–2 July 2011; pp. 643–649.
206. Sacks, R.; Perlman, A.; Barak, R. Construction safety training using immersive virtual reality. *Constr. Manag. Econ.* **2013**, *31*, 1005–1017. [CrossRef]
207. Kim, K.; Kim, H.; Kim, H. Image-based construction hazard avoidance system using augmented reality in wearable device. *Autom. Constr.* **2017**, *83*, 390–403. [CrossRef]
208. Getuli, V.; Giusti, T.; Capone, P.; Sorbi, T.; Bruttini, A. A Project Framework to Introduce Virtual Reality in Construction Health and Safety. *AlmaDL J. New Front. Constr. Manag. Work.* **2018**, *9*, 166–175.
209. Moore, H.F.; Gheisari, M. A Review of Virtual and Mixed Reality Applications in Construction Safety Literature. *Safety* **2019**, *5*, 51. [CrossRef]
210. Hasanzadeh, S.; Polys, N.F.; Garza, J.M. de la Presence, Mixed Reality, and Risk-Taking Behavior: A Study in Safety Interventions. *IEEE Trans. Vis. Comput. Graph.* **2020**, *26*, 2115–2125. [CrossRef] [PubMed]
211. Sampaio, A.Z.; Gomes, A.R.; Santos, J.P. Management of building supported on virtual interactive models: Construction planning and preventive maintenance. *Electron. J. Inf. Technol. Constr.* **2012**, *17*, 121–133.
212. Irizarry, J.; Gheisari, M.; Williams, G.; Walker, B.N. InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach. *Autom. Constr.* **2013**, *33*, 11–23. [CrossRef]
213. Neges, M.; Koch, C. Augmented reality supported work instructions for onsite facility maintenance. In Proceedings of the 23rd International Workshop of the European Group for Intelligent Computing in Engineering EG-ICE 2016, Kraków, Poland, 29 June–1 July 2016; pp. 10–12.
214. Chalhoub, J.; Ayer, S.K. Using Mixed Reality for electrical construction design communication. *Autom. Constr.* **2018**, *86*, 1–10. [CrossRef]
215. Baek, F.; Ha, I.; Kim, H. Augmented reality system for facility management using image-based indoor localization. *Autom. Constr.* **2019**, *99*, 18–26. [CrossRef]
216. Ahn, S.J.; Han, S.U.; Al-Hussein, M. 2D Drawing Visualization Framework for Applying Projection-Based Augmented Reality in a Panelized Construction Manufacturing Facility: Proof of Concept. *J. Comput. Civ. Eng.* **2019**, *33*. [CrossRef]
217. Dong, H.; Xu, G.; Chen, D. Research on Overhead crane training system and its construction based on virtual reality. In Proceedings of the 2010 International Conference on Artificial Intelligence and Education (ICAIE), Hangzhou, China, 29–30 October 2010; pp. 206–209.
218. Sekizuka, R.; Koiwai, K.; Saiki, S.; Yamazaki, Y.; Tsuji, T.; Kurita, Y. A virtual training system of a hydraulic excavator using a remote controlled excavator with augmented reality. In Proceedings of the 2017 IEEE/SICE International Symposium on System Integration (SII), Taipei, Taiwan, 11–14 December 2017; pp. 893–898.
219. Bin, F.; Xi, Z.; Yi, C.; Ping, W.G. Construction safety education system based on virtual reality. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *563*. [CrossRef]
220. Checa, D.; Bustillo, A. A review of immersive virtual reality serious games to enhance learning and training. *Multimed. Tools Appl.* **2020**, *79*, 5501–5527. [CrossRef]
221. Maas, M.J.; Hughes, J.M. Virtual, augmented and mixed reality in K–12 education: A review of the literature. *Technol. Pedagog. Educ.* **2020**, *29*, 231–249. [CrossRef]
222. Dong, S.; Behzadan, A.H.; Chen, F.; Kamat, V.R. Collaborative visualization of engineering processes using tabletop augmented reality. *Adv. Eng. Softw.* **2013**, *55*, 45–55. [CrossRef]

223. Zou, P.X.W.; Zhang, G.; Wang, J. Understanding the key risks in construction projects in China. *Int. J. Proj. Manag.* **2007**, *25*, 601–614. [CrossRef]
224. Mutis, I.; Ambekar, A. Challenges and enablers of augmented reality technology for in situ walkthrough applications. *J. Inf. Technol. Constr.* **2020**, *25*, 55–71. [CrossRef]
225. Andri, C.; Alkawaz, M.H.; Sallow, A.B. Adoption of mobile augmented reality as a campus tour application. *Int. J. Eng. Technol.* **2018**, *7*, 64–69. [CrossRef]
226. Elghaish, F.; Matarneh, S.; Talebi, S.; Kagioglou, M.; Hosseini, M.R.; Abrishami, S. Toward digitalization in the construction industry with immersive and drones technologies: A critical literature review. *Smart Sustain. Built Environ.* **2020**. [CrossRef]
227. Al-Hussein, M. Application of Virtual Reality in Task Training in the Construction Manufacturing Industry. In Proceedings of the 36th International Symposium on Automation and Robotics in Construction 2019, Banff, AB, Canada, 21–24 May 2019; pp. 796–803.