buildings

MDPI

Review

Extended Reality for Safe and Effective Construction Management: State-of-the-Art, Challenges, and Future Directions

Xuefeng Zhao, Meng Zhang, Xiongtao Fan, Zhe Sun *, Mengxuan Li, Wangbing Li and Lingli Huang

Faculty of Architecture, Civil and Transportation Engineering, Beijing University of Technology, Beijing 100124, China
* Correspondence: zhesun@bjut.edu.cn

Abstract: Safe and effective construction management requires tools for reducing delays, eliminating reworks, and avoiding accidents. Unfortunately, challenges still exist in current construction practices for enabling real-time interactions among project participants, field discoveries, and massive data. Extended reality (i.e., XR) could help to establish immersive and interactive virtual environments that enable real-time information exchange among humans, cyber processes, and physical environments during construction. However, limited studies have synthesized potentials, challenges, and scenarios of XR for ensuring construction safety and efficiency. This study provides a critical review that synthesizes XR in construction management. First, the authors used the PRISMA method to screen studies related to XR in construction management. Seventy-nine studies were selected and comprehensively analyzed. The authors conducted a bibliometric analysis to comprehend the spatiotemporal distributions of the selected studies. Then, the selected studies were classified into three categories: (1) progress control, (2) quality control, and (3) safety management. The authors also synthesized information for XR applications in various construction management scenarios and summarized the challenges related to XR applications. Finally, this review shed light on future research directions of XR for safe and effective construction management.

Keywords: virtual reality (VR); augmented reality (AR); mixed reality (MR); construction management

Citation: Zhao, X.; Zhang, M.; Fan, X.; Sun, Z.; Li, M.; Li, W.; Huang, L. Extended Reality for Safe and Effective Construction Management: State-of-the-Art, Challenges, and Future Directions. *Buildings* **2023**, *13*, 155. https://doi.org/10.3390/buildings13010155

Academic Editors: Lei Hou, Jun Wang, Sheng Xu and Rafiq Muhammad Choudhry

Received: 30 November 2022
Revised: 2 January 2023
Accepted: 4 January 2023
Published: 7 January 2023

1. Introduction

Safe and effective construction management is always challenging due to extended construction periods with numerous uncertainties [1]. However, current construction practices could hardly achieve a high level of automation and intelligence, which impede effective and safe construction management processes. For example, time-series sensory data used for quality control and hazard prognosis could hardly be visualized at construction sites. Besides, current safety training programs cannot provide an interactive training environment for workers. Casualties and delays always occur that jeopardize constriction safety and efficiency. It is thus necessary to establish a system that allows real-time visualization and interaction with heterogeneous data and information during tedious construction processes to ensure safe and effective construction management.

Extended reality (XR) represents various immersive technologies that have been developed to improve user experience and enhance their feelings [2]. XR includes virtual reality (VR), augmented reality (AR), and mixed reality (MR) (the spectrum of VR, AR, and MR is shown in Figure 1). As shown in Figure 1, VR focuses on providing a complete virtual immersive environment that isolates the user from the real world. In contrast, AR and MR aim to blend virtual elements with the real environment. Specifically, AR emphasizes the superposition of virtual elements in the real environment. In contrast, MR could help to blend virtual elements and real environments completely. Through MR, users can interact with elements from both real and virtual environments simultaneously, and elements from the real and virtual environments can also interact [3]. VR has the potential to shield from on-site hazards and provide immersive and interactive virtual construction environments. AR and MR have the potential to support on-site information retrieval and access and real-time information transfer [4–6]. As proved by many scholars and industry practitioners, XR could be used as a potential tool to improve the information exchange process among humans, cyber processes, and environments during construction management. At present, XR has been preliminarily applied in the progress inspection [6–8], operation instruction [9–11], quality inspection [12,13], hazard identification [14,15], safety education and training [16,17], safety inspection [18–20], and other aspects of the construction site. Based on the above XR use cases, limitations of XR still exist. It is thus necessary to further improve the existing XR-based techniques for supporting effective control of construction progress, quality, and safety. Specifically, the authors have presented a vision of using XR for safe and effective construction management (shown in Figure 2).

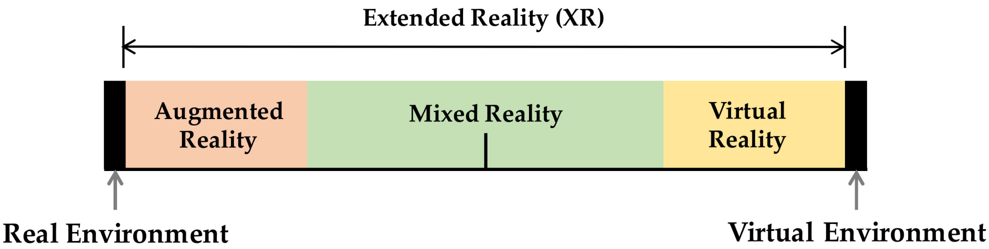


Figure 1. The spectrum of VR, AR, and MR Fields.

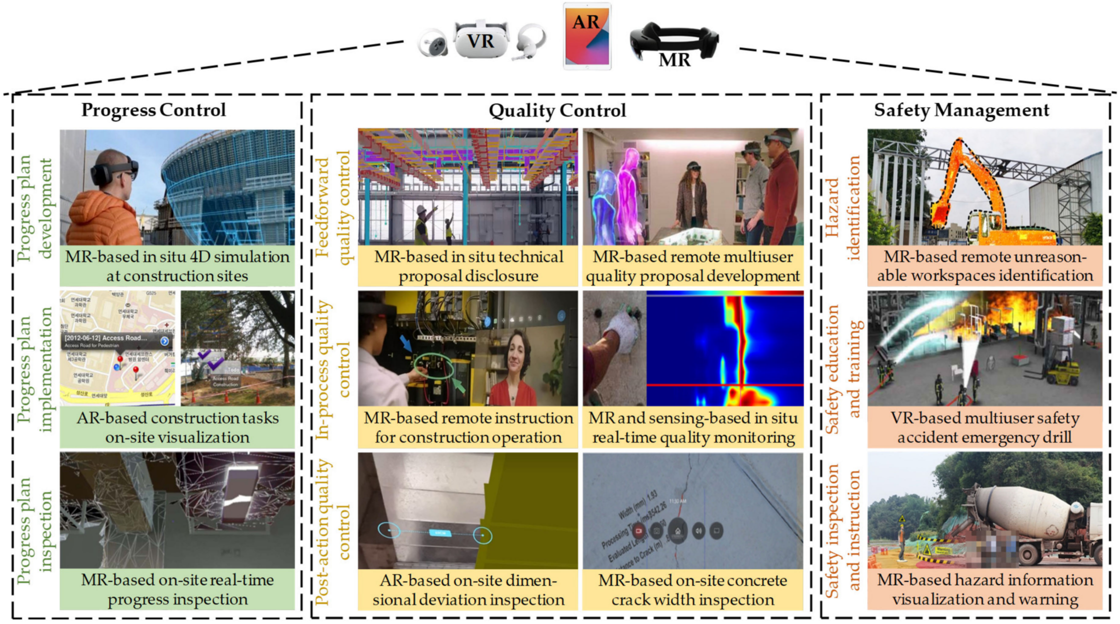


Figure 2. A vision of XR for safe and effective construction management.

XR has been extensively examined by various researchers worldwide and has been adopted in many practical scenarios. There are several review studies on the application of XR in the construction engineering and management domain. For example, Cheng et al. [21] summarized the application of AR and MR in the architecture, engineering, construction, and operation (AECO) industry and analyzed the application status of AR/MR according to the stage division. Khan et al. [22] conducted a SWOT analysis to examine the feasibility of integrating XR and building information modeling (BIM) in the architecture, engineering, and construction (AEC) industry. Zhang et al. [22] conducted a bibliometric analysis of XR that summarized seven research hotspots and future research directions. Zhu et al. [23] summarized the latest applications of VR and AR in emergency management scenarios. Li et al. [24] summarized the uses of VR and AR for construction safety. In summary, previous studies have conducted extensive efforts to examine various XR techniques in numerous engineering scenarios. All such efforts have shown the great potential of using XR techniques to provide field workers and all other project participants with augmented visualization and interactive experiences. Unfortunately, limited studies have synthesized the domain requirements and challenges for achieving safe and effective construction management using XR techniques.

Hence, according to the analysis of Figure 2 and the analysis of existing review studies, it is necessary to have a comprehensive synthesis of potentials, challenges, and use cases of XR in construction management. The major contribution and novelty of this review are synthesizing the requirements, challenges, and use case scenarios of using XR techniques for effective safety control, coordination, and collaboration in the construction management domain. The overall goal of this review is to (1) investigate the spatiotemporal distribution rule of relevant studies, (2) synthesize various XR implementation cases in different construction management scenarios and summarize the challenges related to XR applications, and (3) prospect potential application scenarios and application method improvements of XR in the construction management domain.

The organization of the following sections is as follows. Section 2 illustrates a motivation case by using a production safety accident to demonstrate the limitations of the existing construction management practices. Section 3 collects the studies of XR used in construction management to obtain accurate literature review data. Section 4 synthesizes the current state of XR in construction management based on the selected studies. This section also discusses the practical application challenges of XR for safe and efficient construction management. Section 5 proposes the potential application scenarios and application method improvements of XR for advancing construction management to inform future research activities. Section 6 summarizes the status and challenges of XR for safe and effective construction management.

2. A Motivating Case

According to the Construction Management Association of America (CMAA), construction management is a professional service that provides a project's owner(s) with effective management of the project's progress, quality, safety, and other aspects. However, construction project casualties, progress delays, and quality rework accidents still occur based on the current construction management practices. In this section, the authors selected a typical case of production safety accidents at construction sites published by the Ministry of Emergency Management, PRC, to analyze the limitations of the existing construction management methods (shown in Figure 3).

As shown in Figure 3, a collapse accident of a tower crane occurred in Huarong County, Hunan Province, China. The accident killed five people and caused more than RMB 5.8 million in direct economic losses. Accident reports indicate that the root cause of this accident was workers' illegal disassembly operations, which caused the crane component to fall off. The managerial cause of this kind of accident can be summarized as follows. On the one hand, existing safety training on-site heavily relies on passive teaching methods (e.g., lectures, manuals, and videos). However, all such passive teaching methods lack real experience and could hardly achieve effective safety training for workers [25]. Therefore, it is necessary for the construction management domain to develop effective safety training programs with training environments that are interactive and free of security risks. On the other hand, experienced engineers are limited human resources at construction sites, which creates challenges in providing sufficient supervision and instructions for newly admitted construction personnel, and field engineers cannot fully and accurately detect all hazards and propose solutions on time [26,27]. In addition, the inspected information about quality or safety hazards cannot be directly displayed at construction sites, which leads to the failure of on-site workers to obtain this information [28]. Therefore, it is necessary to study the automatic method of quality control and safety inspection at construction sites and the effective transfer mechanism of risk information.

Figure 3. The analysis of construction management limitations.

Affected by the stoppage or rework of the construction project, this kind of accident can easily cause project delays. In this case, if the traditional progress inspection method is adopted at construction sites (i.e., the inspectors collect progress data from the site and conduct statistical analysis off-site to form progress inspection reports periodically to record the progress), the managers cannot grasp the completion of the site tasks in real-time and decide on schedule adjustments according to the difference between the completion state and the as-planned data [7,8]. Therefore, it is thus necessary to study the method of inspecting progress deviations automatically at construction sites.

This motivating case shows that several challenges impede safe and effective construction management: (1) it is not possible to provide workers with an interactive education and training environment without security risks, (2) experienced engineers are limited human resources at construction sites, which leads to the inability to provide workers with intuitive and correct operation instructions, (3) progress deviation, quality defect, and safety facility defect cannot be inspected automatically in real-time according to the as-planned model and data, and (4) it is not possible to provide on-site workers with intuitive and real-time risk information.

3. Data Collection for the Literature Review

Obtaining accurate literature data related to the topic of this review is essential for analyzing published literature. In this study, the Preferred Reporting Items for Systematic Literature Review and Meta-Analysis (PRISMA) framework was used to collect data. Since its launch in 2009 [29], PRISMA has been cited in more than 60,000 publications (Scopus, May 2022) and has been adopted in various disciplines. Similar studies in review studies published in journals such as the journal of *Automation in Construction* (Elsevier) and the journal of *Buildings* (MDPI) are based on PRISMA's four-stage flow chart for data screening [30–33]. In this study, data screening was carried out according to the PRISMA flow chart updated in 2020 [34], and the data screening process is shown in Figure 4. In addition, the data of the literature search is till May 2022.

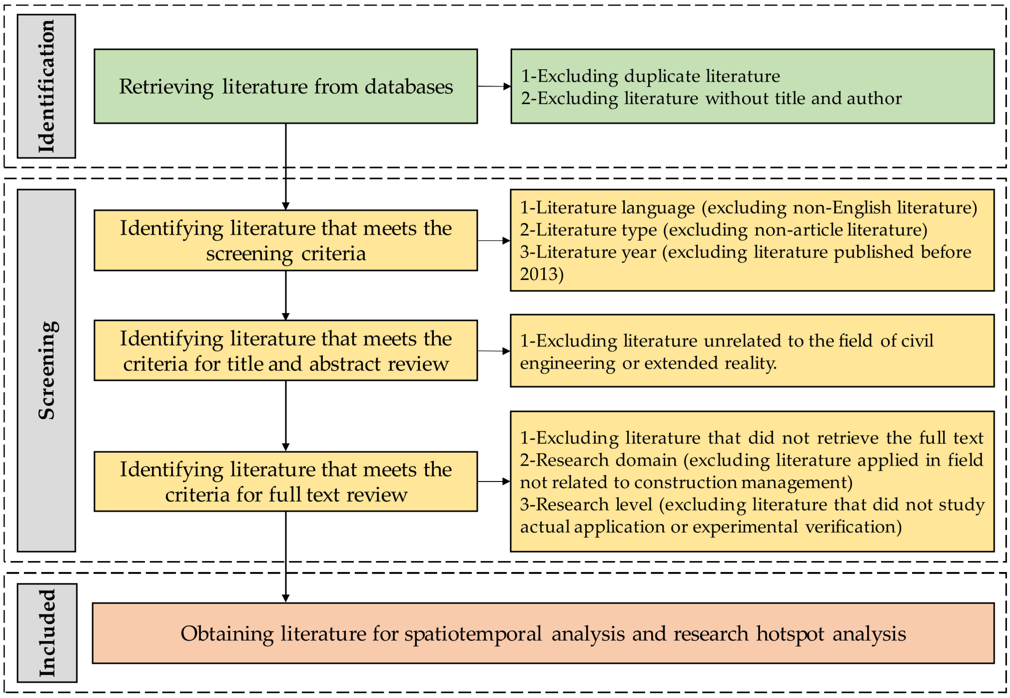


Figure 4. The data screening process.

3.1. Identification

Firstly, Web of Science (WoS), Scopus, and Google Scholar are important databases for obtaining global academic information. However, the literature retrieval and screening methods (e.g., retrieval items, research domain screening, and literature type screening) of Google Scholar are different from those of Web of Science and Scopus. Therefore, in this study, the authors have used the Web of Science and Scopus databases for literature retrieval, and the Google Scholar database is selected for supplementary literature retrieval.

Secondly, the keyword set used to retrieve literature related to the topic of this review is divided into two aspects, one is the keyword set related to "extended reality" (XRK), and the other is the keyword set related to "construction engineering and management" (CRK). Among them, the set of keywords related to "extended reality" was identified as:

XRK = "Immersive* Technology*" OR "Extended reality" OR "XR" OR "Virtual Reality" OR "VR" OR "Augmented Reality" OR "AR" OR "Mixed Reality" OR "MR" OR "virtual environment" OR "virtual prototype*". The wildcard "*" retrieved any keyword with multiple spelling variants. For example, "virtual prototype*" can retrieve two keywords: "virtual prototype" and "virtual prototyping".

The keyword set related to "construction engineering and management" (CRK) involves many topics. In addition, since the purpose of this study is to explore the application status of XR in the construction field of "three control, three management, and one coordination", this study selected keywords not only from the overall perspective of "construction" or "AEC", but also from the perspective of progress, quality, and safety. In this study, the following three methods are combined to select keyword sets: keyword co-occurrence analysis by using Citespace 5.8.R3, reference to previous review articles on extended reality and construction, and professional experience. In the management system of "three control, three management, and one coordination", "information management" focuses on the research of "information management system", "database", and other related aspects [35–37]. The literature retrieved mainly belongs to the field of computer science, and the extended reality itself is the database. "Organizational coordination" belongs to pure management. "Organizational coordination" is mainly related to organizational structure, job responsibilities, and the development of organizational management measures, whereas the extended reality focuses on technical aspects. The above two aspects deviate from the theme of the application of extended reality in construction management, so they are not within the scope of this review. Therefore, the set of keywords related to "construction engineering and management" was finally identified as:

CRK_1 = "construction" OR "AEC" OR "build*" OR "civil engineering*" OR "construction engineering*" OR "engineering*" OR "infrastructure" OR "BIM" OR "building information model*" OR "construction management" OR "project management" OR "built environment" OR "Lean construction" OR "green construction" OR "LEED"

CRK_2 = "progress" OR "schedule" OR "workflow" OR "Critical-path Method" OR "Gantt Chart" OR "CPM" OR "time management"

CRK_3 = "cost" OR "budget" OR "cost estimation" OR "quantity take-off" OR "finance"

CRK_4 = "quality" OR "quality assurance" OR "quality control" OR "QA" OR "QC" OR "building* performance" OR "performance"

CRK_5 = "safe*" OR "Health and Safety"

CRK_6 = "contract*" OR "project delivery" OR "integrated project delivery" OR "Design Bid Built" OR "Design Built" OR "IPD" OR "DBB" OR "DB" OR "EPC"

Thirdly, the research domain used for literature retrieval was limited to the six major subject domains: civil engineering; environmental engineering; geological engineering; construction building technology; transportation science and technology; safety, risk, reliability, and quality.

Finally, the Web of Science and Scopus databases was searched, respectively, according to the following search formula:

TS = ("Immersive* Technology*" OR "Extended reality" OR "Virtual Reality" OR "Augmented Reality" OR "Mixed Reality" OR "XR" OR "VR" OR "AR" OR "MR" OR "virtual prototype*" OR "virtual environment") AND TS = ("construction" OR "AEC" OR "build*" OR "civil engineering*" OR "construction engineering*" OR "engineering*" OR "infrastructure" OR "BIM" OR "building information model*" OR "construction management" OR "project management" OR "built environment" OR "Lean construction" OR "green construction" OR "LEED" OR "progress" OR "schedule" OR "workflow" OR "Critical-path Method" OR "Gantt Chart" OR "CPM" OR "time management" OR "cost" OR "budget" OR "cost estimation" OR "quantity take-off" OR "finance" OR "quality" OR "quality assurance" OR "quality control" OR "QA" OR "QC" OR "building* performance" OR "performance" OR "contract*" OR "project delivery" OR "integrated project delivery" OR "Design Bid Built" OR "Design Built" OR "IPD" OR "DBB" OR "DB" OR "EPC" OR "safe*" OR "Health and Safety") AND SU = ("Construction & Building Technology" OR "Engineering, Civil" OR "Engineering, Environmental" OR "Engineering, Geological" OR "Transportation Science & Technology")

TITLE-ABS-KEY("Immersive* Technology*" OR "Extended reality" OR "Virtual Reality" OR "Augmented Reality" OR "Mixed Reality" OR "XR" OR "VR" OR "AR" OR "MR" OR "virtual prototype*" OR "virtual environment") AND TITLE-ABS-KEY("construction" OR "AEC" OR "build*" OR "civil engineering*" OR "construction engineering*" OR "engineering*" OR "infrastructure" OR "BIM" OR "building information model*" OR "construction management" OR "project management" OR "built environment" OR "Lean construction" OR "green construction" OR "LEED" OR "progress" OR "schedule" OR "workflow" OR "Critical-path Method" OR "Gantt Chart" OR "CPM" OR "time management" OR "cost" OR "budget" OR "cost estimation" OR "quantity take-off" OR "finance" OR "quality" OR "quality assurance" OR "quality control" OR "QA" OR "QC" OR "building* performance" OR "performance" OR "contract*" OR "project delivery" OR "integrated project delivery" OR "Design Bid Built" OR "Design Built" OR "IPD" OR "DBB" OR "DB" OR "EPC" OR "safe*" OR "Health and Safety") AND SUBJTERMS(2215 OR 2205 OR 2305 OR 2213 OR 1909). Among them, 2215; 2205; 2305; 2213; 1909 belong to All Science Journal Classification Codes (ASJC) of the Scopus database. These codes, respectively, stand for building and construction; civil and structural engineering; environmental engineering; safety, risk, reliability, and quality; geotechnical engineering, and engineering geology.

3.2. Screening and Included

Firstly, to limit the year of literature review data, this study retrieved literature from the Web of Science and Scopus databases with XRK as the search keywords, subject as the search item, and research domain in Section 3.1 as the search domain. Figures 5 and 6 show the annual trends of publications obtained from the literature search. The data of the literature search is till May 2022, so the data for 2022 in Figures 5 and 6 is forecast data. Figures 5 and 6 show that the annual trend of published studies in the two databases is the same. Since the turning point in 2012, the number of published studies in the two databases has been consistently over 150 and 600 since 2013 and showing an obvious upward trend. At the same time, to ensure the timeliness of the retrieved literature, the literature years were finally limited to 2013 to 2022.

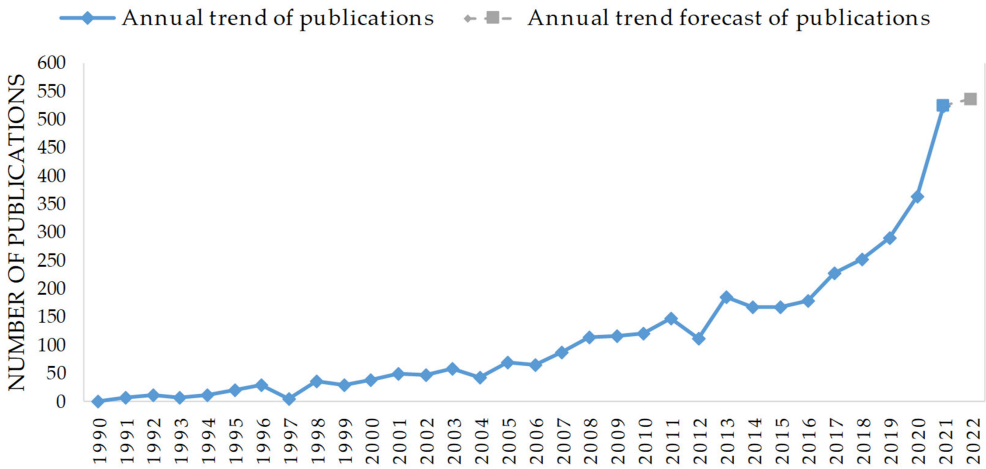


Figure 5. Annual trend of publications of WoS database.

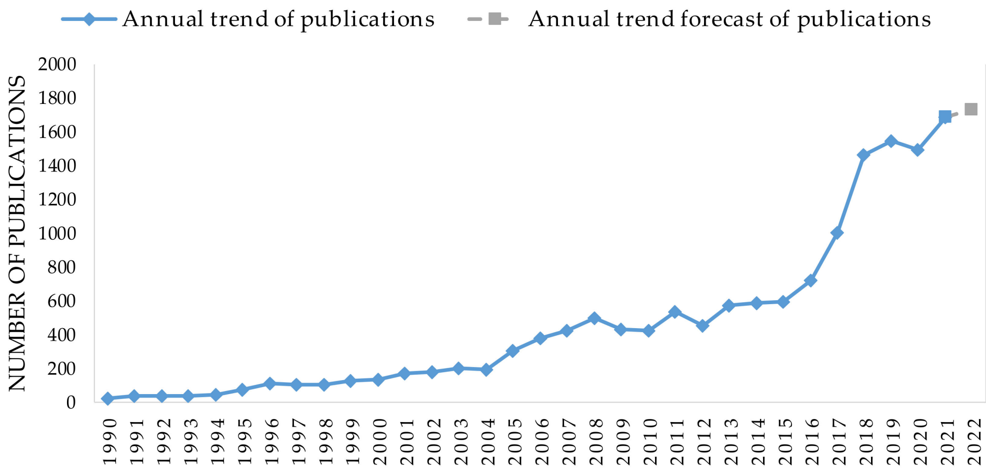


Figure 6. Annual trend of publications of Scopus database.

Secondly, studies with the type of "Article" are comprehensive and detailed elaborations of the latest research results by researchers. Moreover, journal studies will go through several rounds of strict review processes, and this type of literature provides high-quality academic information. Therefore, "Article" is selected for this review. At the same time, this review selected studies from international journals retrieved from the Web of Science and Scopus databases, so the literary language was limited to English.

After preliminary screening, a total of 3710 studies entered the title and abstract review process. According to the noun abbreviations, studies unrelated to construction engineering and management or extended reality were excluded. For example,"-Ar" stands for aromatic compounds occurring in the field of environmental engineering, and "magnetorheological

(MR)" stands for magnetorheological, which has nothing to do with extended reality. After the title and abstract review process, a total of 1208 studies entered the full-text review process. In the full-text review stage, (1) literature in engineering education, landscape design, mechanical design, and other domains unrelated to construction engineering and management will be excluded; (2) literature that only carried out technical development or theoretical framework building without actual application or experimental verification will be excluded. Finally, seventy-two studies from the Web of Science and Scopus databases met the inclusion criteria.

In addition, the authors used the snowballing searching method in Google Scholar (i.e., searching for references and citations of the included studies) [31]. In this study, the authors used the snowballing search method for the above seventy-two included studies to identify six additional studies. The authors also retrieved the studies of the scholar with the largest number of studies on the application of XR in the construction management domain (the retrieved result obtained from Web of Science is scholar Wang), and the authors identified one additional study [38]. Finally, seventy-nine studies (seventy-two were retrieved from Web of Science and Scopus, and seven were supplementarily retrieved from Google Scholar) were included in the following data analysis.

4. Extended Reality for Safe and Effective Construction Management

Through a rigorous review of data sources, the authors have selected seventy-nine studies for further data analysis. Besides, the studies are divided into five categories related to construction management, including progress control, cost control, quality control, contract management, and safety management. Firstly, this study summarized the previous research on the application of extended reality in construction management, and the summary results are shown in Table 1. As can be seen from Table 1, (1) the application of extended reality in contract management of the "three control, three management, and one coordination" system is not reflected in the previous research work, whereas the application in safety management accounted for a very high proportion. In (2) virtual reality has the highest proportion of applications in safety management, whereas mixed reality has a very low proportion of applications in progress control, quality control, and safety management. Secondly, this study analyzed the temporal distribution, spatial distribution (Section 4.1), and research hotspots (Section 4.2) of the included studies.

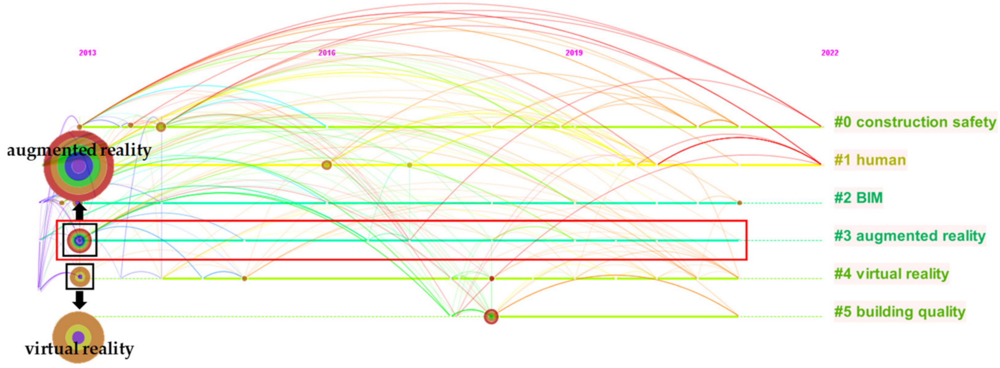
Table 1. The proportion of applications of XR in construction management.

	VR	AR	MR	Summary
Cost control	1.3%	0	0	1.3%
Progress control	1.3%	8.9%	1.3%	11.5%
Quality control	1.3%	18.9%	0	20.2%
Safety management	54.4%	8.9%	3.7%	67%
Summary	58.3%	36.7%	5%	100%

4.1. Spatiotemporal Analysis of XR in Construction Management

4.1.1. Temporal Distribution

Cluster analysis can divide a large number of keywords into several research topics. The timeline analysis of keyword clustering also can consider the effect of time on research clusters. The timeline visualization of keywords can extract two types of information: (1) the first appearance year and duration of keywords and (2) the duration of the research topic. Therefore, the authors analyzed the temporal distribution of the included literature in Section 3 by timeline analysis. The timeline visualization of keyword clustering created by Citespace 5.8.R3 is shown in Figure 7. In this study, the six largest research clusters (#0-#5) were finally determined by the log-likelihood ratio (LLR) algorithm in cluster analysis. It can be seen from Figure 7 that: (1) since the two keywords "virtual reality" and "augmented reality" first appeared in two clusters (#3 and #4) in 2013, they have appeared in the included literature until 2022, which makes the keyword nodes show the characteristics of large nodes and color changes from purple to red. However, the keyword "mixed reality" did not appear in the six largest research clusters. In (2) the figure also shows the duration of each research cluster. For example, the cluster (#3) represented by "augmented reality" covers a period from 2013 to 2021, indicating a series of research results on the application of AR in construction management during these nine years. In summary, Figure 7 shows that VR/AR-related application studies have been hotspots in the construction management domain since 2013.



[1] The node color represents the appearance year of keywords.

2013	2014	2015	2016	2017	2018	2019	2020	2021	2022

[2] The red box represents the duration of the research cluster (#3).

Figure 7. Timeline visualization of keywords.

4.1.2. Spatial Distribution

Analyzing journal sources enables the presentation of influential journals in the research domain. This study visualized the journals where the data included in Section 3 are distributed, and the visualization result is shown in Figure 8. It can be seen from Figure 8 that: studies related to the application of XR in construction management are mainly distributed in the journal of *Automation in Construction*, the *Journal of Computing in Civil Engineering*, *Buildings*, and the *Journal of Construction Engineering and Management*. This result shows that the publications in these journals can provide researchers with the latest research basis.

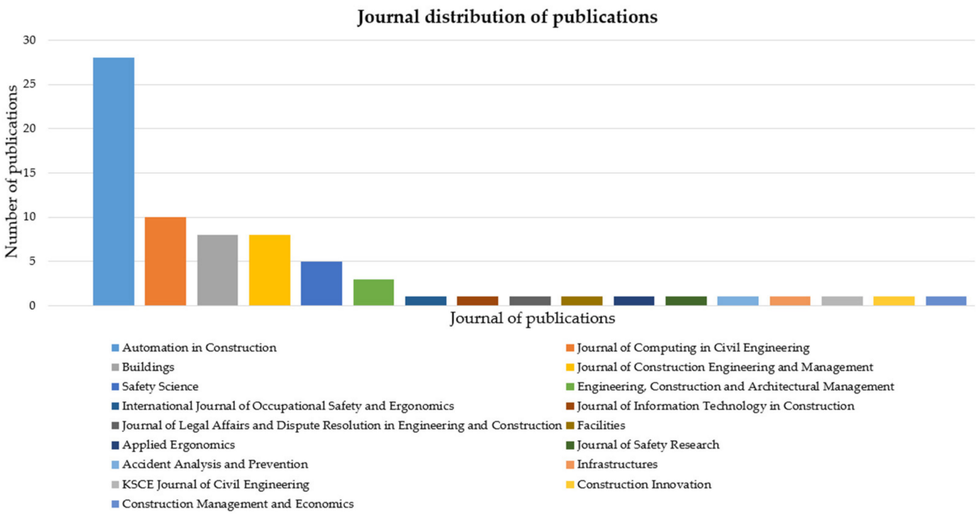


Figure 8. Journal distribution of publications.

4.2. Research Hotspots of XR in Construction Management

The application of XR in contract management is not reflected in the previous research work. The application in cost control is only reflected in one study, which is not analyzed as a separate section. Therefore, the research hotspot analysis was synthesized from progress control, quality control, and safety management. According to these research hotspots, the authors proposed an overall analytical framework from two perspectives: (1) a management perspective and (2) a technical perspective. Specifically, the proposed analytical framework from the management perspective is based on the textbook of the Constructor Examination in China and the related literature on construction management [24,39]. Besides, the proposed analytical framework from the technical perspective is based on the XR technical architecture proposed by the China Academy of Information and Communications Technology (CAICT). The specific analysis framework is shown in Figure 9. In addition, the analysis of each area is carried out from two aspects: (1) state-of-the-art studies of XR applications and (2) challenges related to XR applications.

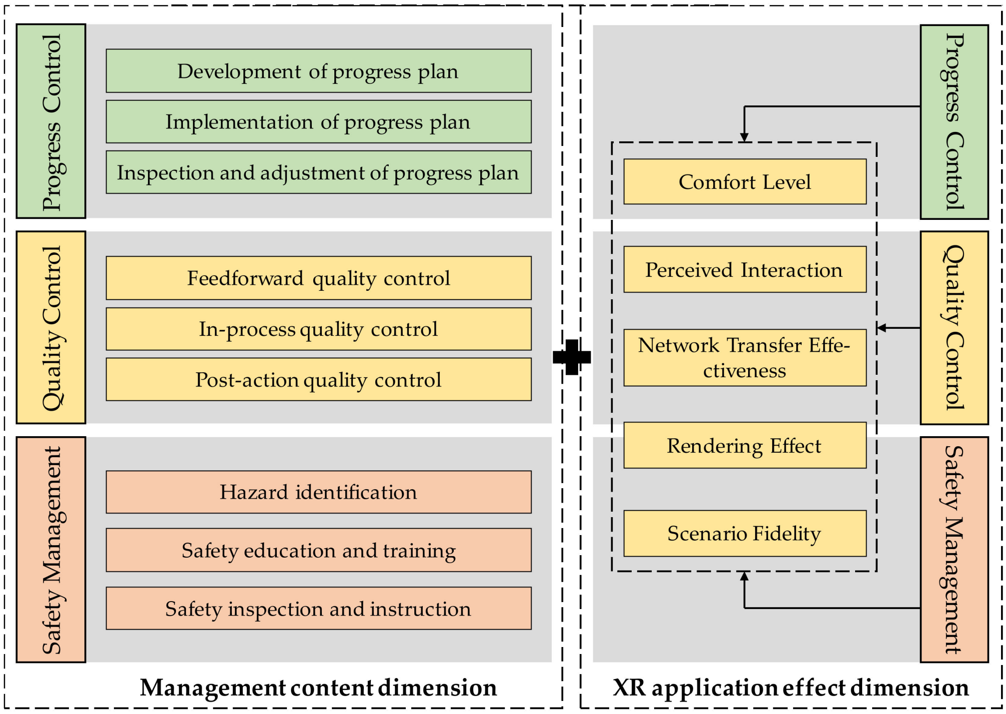


Figure 9. The analytical framework of the research hotspots.

4.2.1. Progress Control

Among the seventy-nine studies included in the analysis, nine studies were related to research topics in progress control. Overall, these relevant studies approach the progress control issues through the visualization of schedule, the automatic inspection of progress deviations, and the on-site visualization of inspection data. Moreover, among the nine XR systems developed in these studies, seven are AR systems, and the other two are VR and MR systems.

- State-of-the-art studies of XR applications

Regarding schedule visualization, on-site workers cannot interact with the 4D model (e.g., measuring distance, inspecting component types), which is not conducive to workers' perception of the workspace [40]. In terms of on-site progress inspection, the traditional progress inspection methods are affected by subjective experience and are not conducive to the real-time grasp of the site progress. To address the issues mentioned above, Tallgren et al. [40] developed a VR-based project planning system that enables users to view and interact with 4D models in an immersive manner. Kopsida and Brilakis [8] proposed an indoor progress inspection method based on MR to inspect the progress deviations automatically. AR has the potential for on-site monitoring, project information retrieval, and real-time information sharing [4–6,41]. Therefore, some researchers have developed

AR applications to realize the in situ presentation of project information and progress inspection data on-site building entities [7,42,43].

The above studies take XR as an in situ visualization tool and interactive tool for construction information. They have examined XR in the following engineering scenarios: (1) an immersive view of the construction process of complex building components and (2) in situ visualization of progress inspection data.

- Challenges related to XR applications

Using XR tools to assist progress control still has some application challenges. For example, Bae et al. [6] tracked and located the position and direction of mobile AR devices by matching the on-site image with the pre-established 3D point cloud model and then enhanced the progress information associated with the building elements in the on-site image. However, this tracking and positioning method has two challenges: (1) high-resolution on-site images are conducive to accurate positioning, but there is a problem with the long matching time between 2D images and 3D point cloud models; (2) if AR devices only include building elements with few feature points (e.g., windows) in the camera's view, the matching accuracy will be low. The above two challenges will lead to the low real-time level and accuracy of the site progress inspection information access. Kopsida and Brilakis [8] inspected whether the 3D objects included in the as-planned model exist in the actual scene by comparing the as-planned data (referring to the pre-established BIM model) with the as-built data (the spatial surface meshes covering the real object captured by MR devices). In this way, the site construction progress can be inspected. However, this inspection method has the following challenges: (1) the accuracy of mesh data captured by MR devices is limited; (2) the scanning results of MR devices are affected by weather conditions, observation angle of the object, and object material type (e.g., tiling, or surfaces with strong light absorption). This inspection method is unsuitable for inspecting small irregular objects' progress, scanning outdoor environments in sunny weather, scanning objects at a shallow angle, and examining the progress of construction tasks related to the material texture. The specific application challenges mentioned in the previous research work in progress control are shown in Table 2.

Table 2. Application challenges related to XR in progress control.

Classification of XR and Its Application Challenges		**Description of Specific Application Challenges**	**References**
AR	Poor perception and interaction	TC_A-1: long matching time between images, resulting in long positioning time of AR and low real-time level of progress information access. TC_A-2: few feature points are included in the camera's view, leading to the low-positioning accuracy of AR devices and the low effectiveness of the enhanced progress information. TC_A-3: the low assisted positioning accuracy of the built-in sensor in mobile AR devices, resulting in large deviations of the enhanced distance information between on-site workers and their work tasks.	[5,6]
	Low efficiency of net-work transfer	TC_A-4: the transfer efficiency of task information between the main database and mobile AR device of on-site engineers is low. TC_A-5: the transfer efficiency of on-site progress information between the main database and the office *manager's* device is low.	[5,7]
MR	Poor perception and interaction	TC_M-1: the quality of mesh data captured by MR devices at construction sites is poor. TC_M-2: the scanning quality is poor when MR devices scan building components at a shallow angle. TC_M-3: the scanning quality is poor when MR devices scan building components under strong light and windy weather conditions. TC_M-4: the scanning quality is poor when MR devices scan building components with reflective surfaces or strong light-absorbing surfaces.	[8]

TC_A-1 represents the first AR-related application challenge and the others are the same.

4.2.2. Quality Control

Among the seventy-nine studies included in the analysis, a total of sixteen studies were related to research topics in quality control. Overall, these relevant studies approach the quality control issues through construction operation instruction and on-site quality inspection. Moreover, among the sixteen XR systems developed in the above studies, fifteen are AR systems, and the other is a VR system. Therefore, this section focuses on the application of AR in quality control.

- State-of-the-art studies of XR applications

Traditional manual-based operating instruction hinders the high integration of workers' information retrieval and understanding and workers' task operation. Traditional quality inspection methods are subjective, time-consuming, and cannot guarantee the accuracy of inspection results. Some researchers proved through experiments that AR can improve the information retrieval process and alleviate the problem of information overload [44]. Hou et al. [9–11,45] developed AR systems to instruct workers in assembly or installation. These systems can improve the effectiveness of operation instruction from the perspective of reducing the number of visual transitions during construction [10] and the obstacles to workers' understanding of complex information [11]. Park et al. [12,46–50] proposed the construction defect inspection method based on BIM and AR, which realized the automatic on-site inspection of the size deviation or omission of building elements. Chi et al. [13,51] developed an AR-based method for inspecting and repairing reinforcement defects, which realized the visualization of reinforcement inspection results and rework instruction. Liu et al. [52] developed a prototype of an AR system to realize the integration of the BIM model and unmanned aerial vehicles (UAVs) aerial video, which can carry out comprehensive quality inspections of buildings.

The above studies take AR as an on-site retrieval tool for quality information. They have examined AR in the following engineering scenarios: (1) in-process instruction of construction quality (e.g., virtual annotations-based on-site assembly or installation instruction), and (2) post-inspection of construction quality (e.g., automatic on-site inspection for dimensional deviations of building entities).

- Challenges related to XR applications

Using XR tools to assist quality control still has some application challenges. For example, Fazel et al. [45,51] found that the field-of-view provided by Helmet Mounted Display (HMD) was limited when they tested the effect of AR tools on workers' assembly instruction. It indicates that using AR instruction tools could limit the ability of workers to perceive their surroundings at complex construction sites. Park et al. [47,49] used the method of combining AR, BIM, and image-matching technology to automatically inspect the defects of building elements caused by size errors at construction sites. However, the effectiveness of the inspection results of this method heavily depends on whether the angle of the cameras of mobile AR devices at construction sites is consistent with the angle of the pre-established standard images. This method has the limitation of low matching accuracy and long matching time between images from different angles. Moreover, this method lacks an effective real-time transfer mechanism of inspection results based on AR annotation between inspectors and on-site workers. Yao et al. [53] combined sensing devices to collect the position information of the impact compactor and carried out real-time visualization on the VR management platform. This method realizes a real-time three-dimensional interactive display for the virtual scene's compaction process to control the operation's quality. However, this method has the limitation of low transfer efficiency of position information between the mobile station of the Beidou Navigation Satellite System, cloud server, and VR management platform. The specific application challenges mentioned in the previous research work in quality control are shown in Table 3.

Table 3. Application challenges related to XR in quality control.

Classification of XR and Its Application Challenges		Description of Specific Application Challenges	References
VR	Low efficiency of net-work transfer	TC_V-1: the low transfer efficiency of position information between sensing devices and VR management platform, resulting in the low real-time level of a 3D interactive display for the compaction process.	[53]
AR	Causing adverse physiological reactions	TC_A-6: head-mounted AR devices provide workers with a limited field of view, resulting in the low perception of the surrounding environment and eyestrain.	[45,51]
	Poor perception and interaction	TC_A-7: large deviation between the angle of the AR images and the angle of the standard images, resulting in low image matching accuracy and low effectiveness of size deviation inspection results. TC_A-8: the path occlusion between the tracking object and the camera, poor lighting conditions, damaged markers, occluded markers, or incorrect attachment positions, failing image matching and alignment of BIM model, or instruction information to the real building component surface.	[9,12,13,47,49,50]
	Low efficiency of net-work transfer	TC_A-9: the real-time transfer efficiency of quality inspection results based on AR annotation between inspectors and on-site workers is low.	[47,50]

TC_V-1 represents the first VR-related application challenge and the others are the same.

4.2.3. Safety Management

The contents of construction safety management include hazard identification and prevention, safety education and training, safety inspection and instruction, and safety accident handling. The typical applications of XR-based construction safety management include three aspects of hazard identification, safety education and training, and safety inspection and instruction [24,39]. Therefore, the studies related to safety incident handling retrieved in this review are limited. Among the seventy-nine studies included in the analysis, fifty-three studies were related to research topics in safety management. Moreover, among the fifty-three XR systems developed in these studies, forty-three are VR systems. These VR systems are used for hazard identification and safety training, and the other AR or MR systems are used for safety inspections.

- State-of-the-art studies of XR applications

1. Hazard identification

The traditional hazard identification methods are challenging to identify unsafe construction environments or unsafe worker behaviors from the perspective of construction participants. The combination of BIM and VR can assess the rationality of a workspace or observe the behavior of construction participants by simulating site conditions and designing immersive interactions. The VR-based safety evaluation method can improve the authenticity of on-site evaluation. For example, Sydora et al. [54–56] developed VR-based crane simulation systems to evaluate the availability of construction space during the lifting process. Getuli et al. [57] used VR to simulate construction activities (e.g., plate installation), which can realize the identification and replanning of unreasonable installation space. In addition, VR plays a stimulus role for the participants. VR can be used to observe the reaction and behavior of construction participants in a virtual hazardous environment and participants are not exposed to the real risk of physical injury [58]. For example, Kurien et al. [14,15,59] create VR construction environments and simulate construction tasks to identify unsafe operating positions by capturing workers' movements during operation. Habibnezhad et al. [60–64] combined VR with physiological sensing to extract the physiological reaction data of workers in virtual hazard scenarios and then form representative priors of unsafe actions. Through experiments, Tixier et al. [62,65] proved that even if workers can correctly identify construction site hazards, they will still engage in dangerous behaviors.

The above studies take VR as a research tool to help the safety management team extract and analyze the potential risks of the construction site to explore how to develop and implement effective safety training and safety inspection plans. They have examined VR in the following engineering scenarios: (1) identifying unsafe operating postures for workers combined with ergonomics, and (2) identifying unreasonable spatial layouts in crane operation.

2. Safety education and training

Traditional online safety education and training methods lack interaction and feedback, whereas on-site safety education and training cannot ensure the safety of workers. Nykanen et al. [66–68] have proved through experiments that VR-based safety education and training can improve workers' safety performance. Therefore, VR-based safety education and training methods are currently advocated, which will not bring any actual risk while improving training effectiveness. Many studies on machinery operation training and construction technology training are based on immersive VR systems [25,69,70]. For example, Song et al. [16,17,71] developed VR-based training systems for workers and machinery to work together. Then, the systems are evaluated from the aspects of system availability and workers' psychological indicators, and the conclusion is that the VR-based safety training system is effective. Joshi et al. [72] developed an immersive VR training system for prestressed concrete construction to train workers in the three aspects of wearing personal protective equipment, avoiding dangerous work areas, and performing tension operations. The above studies are related to the development and evaluation of safety training systems, and the existing studies also involve the formulation and evaluation of safety training content. For example, Shi et al. [73,74] proposed that theories (e.g., cognitive retrieval and memory method and positive reinforcement learning theory) could be embedded in the safety training content to enhance the training effectiveness.

The above studies use the assumed construction scenarios in VR systems to convey abstract safety knowledge to workers to enhance workers' perceptions of hazard sources and understanding of safe behaviors. They have examined VR in the following engineering scenarios: (1) VR safety experience pavilion and (2) construction machinery (e.g., crane, forklift) operation training and construction technology training.

3. Safety inspection and instruction

Safety inspection mainly refers to the inspectors inspecting the conditions of workers, equipment, and environment during construction and conveying risk information to workers on time [24]. Traditional safety inspection methods are affected by the subjective experience of safety inspectors, and the effectiveness of risk information transfer between inspectors and on-site workers is low. Therefore, some studies have studied automated methods for on-site safety inspections. For example, Atherinis et al. [26,75] proposed a VR/AR-based method of automatic inspection of collective protective equipment (CPE), which can improve the accuracy of inspecting the number or location of equipment components. Chen et al. [76] integrated AR, BIM, and path planning into the crane remote operation system, which can automatically identify potential risks (e.g., overload) and issue warnings. Fenais et al. [77,78] developed VR/AR-based mobile platforms to capture information about underground facilities, which can inspect whether the earthwork excavation route will pose a threat to underground facilities in real time. Dong et al. [79,80] combined VR systems, sensing devices, and real-time positioning systems to realize real-time inspection of workers' unsafe behaviors (e.g., misuse of personal protective equipment (PPE)). Promoting the real-time transfer of risk information and visual interaction for safety inspection is also important. Wu et al. [18,19] developed AR/MR-based real-time alarm systems to provide workers with real-time safety warnings in environmental vision to help them determine their safety conditions.

The above studies use XR tools to automatically inspect safety facilities at construction sites and enhance hazard information in the real environment. They have examined VR/AR/MR in the following engineering scenarios: (1) automatic inspection of collective protective equipment, (2) monitoring and warning of unsafe personal conditions, and (3) in situ real-time visualization of underground public facility information.

- Challenges related to XR applications

Using XR tools to assist safety management still has some application challenges. For example, Shi et al. [15,74] used the vision-based motion capture method to capture the movement information of workers working in VR environments to identify unsafe operating postures. However, this method has limitations of occlusion, motion range limited by sensor depth range, and motion speed limited. Pooladvand et al. [55,70] allowed workers to perform operations (e.g., lifting tasks and handling construction material) in the VR system to identify unreasonable workspaces at construction sites (e.g., the potential collision between lifting objects and surrounding objects) and unsafe behaviors of workers (e.g., cutting into dangerous areas). However, the VR system can only provide visual stimulation for users and only support single-user and single-device interaction. This system has limitations of lack of auditory and tactile feedback and not supporting multiuser interaction with multiple devices simultaneously. Kim et al. [19] transformed and matched the workers' perspective image captured by wearable AR devices with the global perspective image captured by the construction site camcorders to track and locate the position and direction of AR devices. This study has calculated, extracted, and enhanced the hazard information of the distance between the workers and the dangerous equipment and the direction of the dangerous equipment relative to the workers. However, challenges still exist, such as large errors of image transformation from different perspectives, occlusion, and high dependence on network and computing systems. These challenging problems could reduce the effectiveness of hazard information and its real-time transfer. Ramos-Hurtado et al. [26] used mobile AR devices to compare the BIM model of Collective Protective Equipment (CPE) with the real elements at construction sites to inspect whether the safety equipment exists. However, in this method, the positioning of the BIM model is realized by manual placement after planeDetection with mobile AR devices, which has the limitation of low positioning accuracy of the model. This method is not suitable for inspecting the size of safety equipment. Wu et al. [18] used MR to anchor the virtual hazard warning sign and the real hazard source to transfer hazard information to on-site workers. However, this method has not realized the automatic alignment between virtual signs and real hazard sources and the sharing of spatial coordinates among different MR devices. The specific application challenges mentioned in the previous research work in safety management are shown in Table 4.

The above analysis has obtained the specific application challenges related to XR in the construction management domain. Finally, it is necessary to summarize and rank these application challenges mentioned in the previous research work, aiming to find the key application challenges and pave the way for the analysis of the future research direction of XR in Section 5. According to the proportion results, the highest-ranking application challenges mentioned in the previous research work are poor perception and interaction of XR. In addition, other challenges of XR include (1) adverse physiological reactions to users (e.g., dizziness), (2) The differences between the virtual scenarios and the real world are still large, and so on. Table 5 shows the summary and ranking of application challenges related to XR in construction management.

Table 4. Application challenges related to XR in safety management.

Classification of XR and Its Application Challenges		Description of Specific Application Challenges	References
VR	Causing adverse physiological reactions	TC_v-2: a long time of VR-based safety education and training for workers, resulting in simulation sicknesses (e.g., dizziness, eyestrain).	[16,17,72,74]
	Poor perception and interaction	TC_v-3: the fast movement speed of workers, the ultra-sensing range of motion, or the occlusion of motion results in the low accuracy of the motion information capture method. TC_V-4: the VR-based safety education and training systems lack auditory feedback and tactile feedback to the trainees. TC_V-5: VR-based crane simulator does not support simultaneous interaction between multiple users and multiple devices.	[14,15,54,55,70,74]
	Large differences between virtual and real scenarios	TC_V-6: the VR training environment does not consider the weather variables and the background sound of the construction site.	[55,70]
AR	Poor perception and interaction	TC_A-10: large transformation and matching errors between images from different perspectives result in low positioning accuracy for AR devices and low effectiveness of hazard information. TC_A-11: the low assisted positioning accuracy of mobile AR devices' built-in sensors results in a large deviation in the enhanced positioning information of underground facilities. TC_A-12: the low scanning accuracy of mobile AR devices or the low operation level of inspectors results in the low positioning accuracy of the virtual model at the construction site.	[19,26,77]
	Low efficiency of network transfer	TC_A-13: the lack of a powerful computing system and high-speed network system results in the failure of the construction hazard avoidance system based on AR and video surveillance.	[19]
MR	Poor perception and interaction	TC_M-5: the automatic alignment between virtual hazard information and real hazard sources and the sharing of spatial coordinates between different MR devices are not realized.	[18]

TC_V-2 represents the second VR-related application challenge and the others are the same.

Table 5. Summary and ranking of application challenges related to XR in construction management.

Classification of XR and Its Application Challenges		Description of Specific Application Challenges	Literature Proportion Ranking
VR	Causing adverse physiological reactions	TC_V-2	2
	Poor perception and interaction	TC_V-3, TC_V-4, TC_V-5	1
	Low efficiency of network transfer	TC_V-1	4
	Large differences between virtual and real scenarios	TC_V-6	3
AR	Causing adverse physiological reactions	TC_A-6	3
	Poor perception and interaction	TC_A-1, TC_A-2, TC_A-3, TC_A-7, TC_A-8, TC_A-10, TC_A-11, TC_A-12	1
	Low efficiency of network transfer	TC_A-4, TC_A-5, TC_A-9, TC_A-13	2
MR	Poor perception and interaction	TC_M-1, TC_M-2, TC_M-3, TC_M-4, TC_M-5	1

Literature proportion ranking represents the respective ranking of VR, AR, and MR.

5. Future Directions of Extended Reality for Advancing Construction Management

Meeting construction management domain requirements and addressing the above XR application challenges in Section 4 will ensure construction management safety and effectiveness. This study proposes future research directions of XR in the construction management domain, which mainly include two parts: (1) extending application scenarios of XR to meet domain requirements and (2) improving application methods of XR to shield the limitations of technologies themselves.

5.1. Future Directions of VR Development for Safe and Effective Construction Management

In the future, the application scenarios of VR in the construction safety management domain can be further extended. Multiuser safety emergency drill is an important part of safety training. VR could simulate large-scale safety accidents and rehearse various dangerous scenarios. VR enables construction workers to better experience an accident scenario and enables safety managers to train workers to use the right escape tools, choose the proper escape routes, and properly cooperate with others. Safety emergency drills can improve workers' response to a real accident site. The following area could be further researched in the future:

- What kind of VR-based multiuser safety emergency training and safety emergency drill plans should be developed and tested?

The following key research concerns need to be addressed in the future to address the above challenges shown in Table 5 and promote VR to play a high value in construction management.

- Quantify and mitigate the effects of adverse physiological reactions: how to comprehensively consider the physiological factors of the trainees (e.g., dizziness) to improve the comfort of VR training and extend the safety training time?
- Enhance perception and interaction: (1) How to embed tactile and auditory feedback mechanisms into VR safety training systems to enhance the training effect? (2) How to combine vision-based motion capture technology with other motion capture methods to capture the motion information of workers working in VR environments and provide a complete set of identification methods for unsafe working posture recognition?
- Reduce the differences between the virtual and the real scenarios: how to add dynamic factors (e.g., real-time weather factors) to the VR safety training environment to improve the fidelity of the training environment and enhance the safety training effect?

5.2. Future Directions of AR Development for Safe and Effective Construction Management

In the future, the application scenarios of AR in the construction quality control domain can be further extended. AR has great application potential in the feedforward disclosure of the technical construction proposal and the various post-action inspections of construction quality (e.g., appearance quality defects of building entities). In addition, although the current applications of AR in cost control are almost blank, the potential of AR for information retrieval and sharing at construction sites still provides opportunities for real-time on-site access to cost information. The following areas could be further researched in the future:

- What kind of AR-based intelligent recognition methods of atlas or drawings should be developed and tested?
- What kind of AR-based inspection methods for appearance quality defects of building entities (e.g., voids and pits) should be developed and tested?
- What kind of AR-based real-time on-site access mechanism for construction information (e.g., scheduling deviations and cost information) should be developed?

The following key research concerns need to be addressed in the future to address the above challenges shown in Table 5 and promote AR to play a high value in construction management.

- Enhance perception and interaction: (1) How to quantify the effects of the occluded or damaged area of markers, scanning angle deviation, or reflective level on the effectiveness of AR registration to accurately identify markers even when markers are occluded or reflective? (2) How to select the appropriate matching points and combine image processing algorithms to simplify the transformation and matching process between AR images and other view images to improve the accuracy of AR device positioning and construction information matching? (3) How to combine the built-in sensor-assisted positioning methods with other positioning methods to improve the positioning accuracy of AR devices to improve the accuracy of enhanced position information? (4) How to select appropriate plane feature points and automatically locate the BIM model at the construction site to improve the accuracy of comparing the BIM model and the real building elements?

- Improve the efficiency of network transfer: how to improve the transfer efficiency of various inspection information between mobile AR devices and master database servers and provide an efficient set of real-time information transfer mechanisms?

5.3. Future Directions of MR Development for Safe and Effective Construction Management

MR combines the advantages of VR and AR to achieve a complete blending of virtual construction elements and the physical construction site. Therefore, compared with the applications of VR and AR, MR has great potential in the progress control, quality control, and safety management domain. The potential application scenarios of MR in construction management are shown in Table 6. Future studies need to be conducted to address the challenges listed in Table 5.

- Enhance perception and interaction: (1) How to resist the interference of weather conditions to apply MR device scanning to outdoor construction scenarios? (2) How to quantify the relationship between the scanning angle or the level of material reflection or illumination intensity and the scanning quality of MR devices to achieve high scanning quality under the condition of shallow scanning angle or reflective surface? (3) How to use the spatial anchor to realize automatic alignment between virtual hazard information and real hazard sources and share spatial coordinates among different local/remote MR devices to realize remote collaboration?

Table 6. Potential application scenarios of MR in construction management.

Classification of the Construction Management Domain		Potential Applications of Mixed Reality
Progress Control	Development of progress plans	• In situ simulation of construction progress at construction sites
	Inspection and adjustment of progress plans	• Real-time automatic inspection of progress deviations at construction sites
Quality Control	Feedforward quality control	• Local/remote multiuser collaboration of construction quality proposal development • In situ disclosure of technical construction proposal
	In-process quality control	• Remote professional instruction for construction operations • In situ real-time monitoring of covert engineering construction quality by connecting sensor data
	Post-action quality control	• In situ inspection of crack width in building entities at construction sites
Safety Management	Hazard identification	• Remote identifying unreasonable workspaces by in situ simulation of mechanical motion at construction sites
	Safety inspection and instruction	• Real-time visualization and warning of the indoor thermal environment of living facilities at construction sites • Real-time visualization and warning of indoor air quality of living facilities at construction sites

6. Conclusions

Implementations of XR provide the capability to interact with construction management information at construction sites. Such implementations could help ensure construction safety and effectiveness by improving the information exchange process among humans, cyber processes, and environments. Nonetheless, several challenges remain to be solved in applying XR in construction engineering and management. In this study, the applications of XR in progress control, quality control, and safety management were synthesized for comprehending domain requirements, application challenges, and potential uses of XR for advancing current practices of construction management. Specifically, this study draws the following conclusions.

- At the management level, XR has the highest application rate in safety management; at the technical level, VR has the highest application rate. In addition, the application results of AR in progress control or quality control have been stable since 2013. In contrast, the application of MR in construction management is still in the preliminary development stage.
- Despite the great potential of XR in the construction management domain, challenges still exist for the extensive use of XR in complex construction management scenarios at present. XR application also has blank spots in scenarios such as in situ real-time inspection of construction quality of covert engineering and remote multiuser collaboration of construction operations.
- Key challenges of implementing XR in construction management include (1) the adverse physiological effects of VR devices on trainees, (2) the low tracking and registration accuracy of AR devices, and (3) the poor environmental perception ability of MR devices in complex and harsh construction environments. All such challenges hinder the large-range applications of XR in construction management.
- Regarding the above application challenges, this study also proposes the future directions of XR for advancing construction management from the two dimensions of potential application scenarios and application method improvements. In the future, it is necessary to study the application methods of a broader range of XR-based scenarios, such as real-time inspection of covert engineering construction and remote multiuser collaboration of construction operations. In addition, it is necessary to study efficient perceived interaction mechanisms of XR to resist the interference of harsh construction environments. In conclusion, the research results of this study will promote the broader application of XR in construction engineering and management. However, limitations still exist in this study. The data collection method used in this study may not guarantee the full coverage of studies worth reviewing, and the authors will focus on more advanced data collection methods. In addition, the authors will pay more attention to scientometric analysis in the future.

Author Contributions: Conceptualization, X.Z.; methodology, X.Z.; data curation, M.Z. and X.F.; software, W.L.; validation, W.L. and L.H.; formal analysis, X.F. and M.L.; investigation, M.L. and L.H.; resources, X.Z., M.Z., X.F. and Z.S.; writing—original draft, M.Z. and Z.S; writing—review and editing, M.Z., Z.S. and M.L.; supervision, X.Z.; funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the sub-committee of teaching guidance for engineering management and engineering cost of Ministry of Education of the People's Republic of China, grant number CMPC202129.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to express their utmost gratitude to the sub-committee of teaching guidance for engineering management and engineering cost of Ministry of Education of the People's Republic of China, grant number CMPC202129 for funding this research, and to Beijing University of Technology for administrative and technical support. Besides, the authors also thank all participants who shared their knowledge to validate and verify this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xu, H.; Chang, R.; Pan, M.; Li, H.; Liu, S.; Webber, R.J.; Zuo, J.; Dong, N. Application of Artificial Neural Networks in Construction Management: A Scientometric Review. *Buildings* **2022**, *12*, 952. [CrossRef]
2. Alizadehsalehi, S.; Hadavi, A.; Huang, J.C. From BIM to Extended Reality in AEC Industry. *Autom. Constr.* **2020**, *116*, 103254. [CrossRef]
3. Flavián, C.; Ibáñez-Sánchez, S.; Orús, C. The Impact of Virtual, Augmented and Mixed Reality Technologies on the Customer Experience. *J. Bus. Res.* **2019**, *100*, 547–560. [CrossRef]
4. 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]

5. Kim, C.; Park, T.; Lim, H.; Kim, H. On-Site Construction Management Using Mobile Computing Technology. *Autom. Constr.* **2013**, *35*, 415–423. [CrossRef]
6. 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]
7. Ratajczak, J.; Riedl, M.; Matt, D.T. BIM-Based and AR Application Combined with Location-Based Management System for the Improvement of the Construction Performance. *Buildings* **2019**, *9*, 118. [CrossRef]
8. Kopsida, M.; Brilakis, I. Real-Time Volume-to-Plane Comparison for Mixed Reality–Based Progress Monitoring. *J. Comput. Civ. Eng.* **2020**, *34*, 04020016. [CrossRef]
9. Hou, L.; Wang, X.; Truijens, M. Using Augmented Reality to Facilitate Piping Assembly: An Experiment-Based Evaluation. *J. Comput. Civ. Eng.* **2015**, *29*, 05014007. [CrossRef]
10. 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]
11. Wang, X.; Truijens, M.; Hou, L.; Wang, Y.; Zhou, Y. Integrating Augmented Reality with Building Information Modeling: Onsite Construction Process Controlling for Liquefied Natural Gas Industry. *Autom. Constr.* **2014**, *40*, 96–105. [CrossRef]
12. Chalhoub, J.; Ayer, S.K.; McCord, K.H. Augmented Reality to Enable Users to Identify Deviations for Model Reconciliation. *Buildings* **2021**, *11*, 77. [CrossRef]
13. Chi, H.L.; Kim, M.K.; Liu, K.Z.; Thedja, J.P.P.; Seo, J.; Lee, D.E. Rebar Inspection Integrating Augmented Reality and Laser Scanning. *Autom. Constr.* **2022**, *136*, 104183. [CrossRef]
14. Barkokebas, R.D.; Li, X. Use of Virtual Reality to Assess the Ergonomic Risk of Industrialized Construction Tasks. *J. Constr. Eng. Manag.* **2021**, *147*, 04020183. [CrossRef]
15. Kurien, M.; Kim, M.K.; Kopsida, M.; Brilakis, I. Real-Time Simulation of Construction Workers Using Combined Human Body and Hand Tracking for Robotic Construction Worker System. *Autom. Constr.* **2018**, *86*, 125–137. [CrossRef]
16. Adami, P.; Rodrigues, P.B.; Woods, P.J.; Becerik-Gerber, B.; Soibelman, L.; Copur-Gencturk, Y.; Lucas, G. Impact of VR-Based Training on Human–Robot Interaction for Remote Operating Construction Robots. *J. Comput. Civ. Eng.* **2022**, *36*, 04022006. [CrossRef]
17. Dhalmahapatra, K.; Maiti, J.; Krishna, O.B. Assessment of Virtual Reality Based Safety Training Simulator for Electric Overhead Crane Operations. *Saf. Sci.* **2021**, *139*, 105241. [CrossRef]
18. Wu, S.; Hou, L.; Zhang, G.; Chen, H. Real-Time Mixed Reality-Based Visual Warning for Construction Workforce Safety. *Autom. Constr.* **2022**, *139*, 104252. [CrossRef]
19. 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]
20. Catbas, F.N.; Luleci, F.; Zakaria, M.; Bagci, U.; LaViola, J.J.; Cruz-Neira, C.; Reiners, D. Extended Reality (XR) for Condition Assessment of Civil Engineering Structures: A Literature Review. *Sensors* **2022**, *22*, 9560. [CrossRef]
21. 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*, 03119009. [CrossRef]
22. Khan, A.; Sepasgozar, S.; Liu, T.; Yu, R. Integration of Bim and Immersive Technologies for Aec: A Scientometric-swot Analysis and Critical Content Review. *Buildings* **2021**, *11*, 126. [CrossRef]
23. Zhang, Y.; Liu, H.; Kang, S.C.; Al-Hussein, M. Virtual Reality Applications for the Built Environment: Research Trends and Opportunities. *Autom. Constr.* **2020**, *118*, 103311. [CrossRef]
24. Zhu, Y.; Li, N. Virtual and Augmented Reality Technologies for Emergency Management in the Built Environments: A State-of-the-Art Review. *J. Saf. Sci. Resil.* **2021**, *2*, 1–10. [CrossRef]
25. 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]
26. Vahdatikhaki, F.; El Ammari, K.; Langroodi, A.K.; Miller, S.; Hammad, A.; Doree, A. Beyond Data Visualization: A Context-Realistic Construction Equipment Training Simulators. *Autom. Constr.* **2019**, *106*, 102853. [CrossRef]
27. Ramos-Hurtado, J.; Muñoz-La Rivera, F.; Mora-Serrano, J.; Deraemaeker, A.; Valero, I. Proposal for the Deployment of an Augmented Reality Tool for Construction Safety Inspection. *Buildings* **2022**, *12*, 500. [CrossRef]
28. Perlman, A.; Sacks, R.; Barak, R. Hazard Recognition and Risk Perception in Construction. *Saf. Sci.* **2014**, *64*, 13–21. [CrossRef]
29. 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]
30. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *BMJ* **2009**, *339*, 332–336. [CrossRef]
31. Sidani, A.; Dinis, F.M.; Duarte, J.; Sanhudo, L.; Calvetti, D.; Baptista, J.S.; Martins, J.P.; Soeiro, A. Recent Tools and Techniques of BIM-Based Augmented Reality: A Systematic Review. *J. Build. Eng.* **2021**, *42*, 102500. [CrossRef]
32. Prabhakaran, A.; Mahamadu, A.M.; Mahdjoubi, L. Understanding the Challenges of Immersive Technology Use in the Architecture and Construction Industry: A Systematic Review. *Autom. Constr.* **2022**, *137*, 104228. [CrossRef]
33. Reja, V.K.; Varghese, K.; Ha, Q.P. Computer Vision-Based Construction Progress Monitoring. *Autom. Constr.* **2022**, *138*, 104245. [CrossRef]

34. Page, M.J.; Moher, D.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. PRISMA 2020 Explanation and Elaboration: Updated Guidance and Exemplars for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n160. [CrossRef] [PubMed]
35. Sun, J.; Lei, K.; Cao, L.; Zhong, B.; Wei, Y.; Li, J.; Yang, Z. Text Visualization for Construction Document Information Management. *Autom. Constr.* **2020**, *111*, 103048. [CrossRef]
36. Sheng, D.; Ding, L.; Zhong, B.; Love, P.E.D.; Luo, H.; Chen, J. Construction Quality Information Management with Blockchains. *Autom. Constr.* **2020**, *120*, 103373. [CrossRef]
37. Pan, X.; Zhong, B.; Sheng, D.; Yuan, X.; Wang, Y. Blockchain and Deep Learning Technologies for Construction Equipment Security Information Management. *Autom. Constr.* **2022**, *136*, 104186. [CrossRef]
38. Hou, L.; Wang, X. A Study on the Benefits of Augmented Reality in Retaining Working Memory in Assembly Tasks: A Focus on Differences in Gender. *Autom. Constr.* **2013**, *32*, 38–45. [CrossRef]
39. Park, C.S.; Kim, H.J. A Framework for Construction Safety Management and Visualization System. *Autom. Constr.* **2013**, *33*, 95–103. [CrossRef]
40. Tallgren, M.V.; Roupé, M.; Johansson, M. 4D Modelling Using Virtual Collaborative Planning and Scheduling. *J. Inf. Technol. Constr.* **2021**, *26*, 763–782. [CrossRef]
41. Rahimian, F.P.; 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]
42. 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]
43. Zaher, M.; Greenwood, D.; Marzouk, M. Mobile Augmented Reality Applications for Construction Projects. *Constr. Innov.* **2018**, *18*, 152–166. [CrossRef]
44. 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]
45. Fazel, A.; Izadi, A. An Interactive Augmented Reality Tool for Constructing Free-Form Modular Surfaces. *Autom. Constr.* **2018**, *85*, 135–145. [CrossRef]
46. Thomas, B.H.; Ochoa, J.J.; Gu, N.; Walsh, J.; Smith, R.T. The Identification, Development, and Evaluation of BIM-ARDM—A BIM-Based AR Defect Management System for Construction Inspections. *Buildings* **2022**, *12*, 140.
47. 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]
48. Hernández, J.L.; Lerones, P.M.; Bonsma, P.; van Delft, A.; Deighton, R.; Braun, J.D. An IFC Interoperability Framework for Self-Inspection Process in Buildings. *Buildings* **2018**, *8*, 32. [CrossRef]
49. 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]
50. Zhou, Y.; Luo, H.; Yang, Y. Implementation of Augmented Reality for Segment Displacement Inspection during Tunneling Construction. *Autom. Constr.* **2017**, *82*, 112–121. [CrossRef]
51. Abbas, A.; Seo, J.; Kim, M. Impact of Mobile Augmented Reality System on Cognitive Behavior and Performance during Rebar Inspection Tasks. *J. Comput. Civ. Eng.* **2020**, *34*, 04020050. [CrossRef]
52. Liu, D.; Xia, X.; Chen, J.; Li, S. Integrating Building Information Model and Augmented Reality for Drone-Based Building Inspection. *J. Comput. Civ. Eng.* **2021**, *35*, 04020073. [CrossRef]
53. Yao, Y.-P.; Ruan, Y.-Z.; Chen, J.; Geng, Y.; Zhang, X.; Liu, B.-Y.; Zong, X.-P.; Yu, G.-Z. Research on a Real-Time Monitoring Platform for Compaction of High Embankment in Airport Engineering. *J. Constr. Eng. Manag.* **2018**, *144*, 04017096. [CrossRef]
54. Sydora, C.; Lei, Z.; Siu, M.F.F.; Han, S.H.; Hermann, U. Critical Lifting Simulation of Heavy Industrial Construction in Gaming Environment. *Facilities* **2021**, *39*, 113–131. [CrossRef]
55. Pooladvand, S.; Taghaddos, H.; Eslami, A.; Nekouvaght Tak, A.; Hermann, U. Evaluating Mobile Crane Lift Operations Using an Interactive Virtual Reality System. *J. Constr. Eng. Manag.* **2021**, *147*, 04021154. [CrossRef]
56. Zhang, Z.; Pan, W. Virtual Reality Supported Interactive Tower Crane Layout Planning for High-Rise Modular Integrated Construction. *Autom. Constr.* **2021**, *130*, 103854. [CrossRef]
57. Getuli, V.; Capone, P.; Bruttini, A.; Isaac, S. BIM-Based Immersive Virtual Reality for Construction Workspace Planning: A Safety-Oriented Approach. *Autom. Constr.* **2020**, *114*, 103160. [CrossRef]
58. Li, N.; Du, J.; González, V.A.; Chen, J. Methodology for Extended Reality–Enabled Experimental Research in Construction Engineering and Management. *J. Constr. Eng. Manag.* **2022**, *148*, 04022106. [CrossRef]
59. Akanmu, A.A.; Olayiwola, J.; Ogunseiju, O.; McFeeters, D. Cyber-Physical Postural Training System for Construction Workers. *Autom. Constr.* **2020**, *117*, 103272. [CrossRef]
60. Noghabaei, M.; Han, K.; Albert, A. Feasibility Study to Identify Brain Activity and Eye-Tracking Features for Assessing Hazard Recognition Using Consumer-Grade Wearables in an Immersive Virtual Environment. *J. Constr. Eng. Manag.* **2021**, *147*, 04021104. [CrossRef]
61. Subedi, S.; Pradhananga, N.; Ergun, H. Monitoring Physiological Reactions of Construction Workers in Virtual Environment: Feasibility Study Using Noninvasive Affective Sensors. *J. Leg. Aff. Disput. Resolut. Eng. Constr.* **2021**, *13*, 04521016. [CrossRef]

62. Jeon, J.H.; Cai, H. Classification of Construction Hazard-Related Perceptions Using: Wearable Electroencephalogram and Virtual Reality. *Autom. Constr.* **2021**, *132*, 103975. [CrossRef]
63. Habibnezhad, M.; Puckett, J.; Jebelli, H.; Karji, A.; Fardhosseini, M.S.; Asadi, S. Neurophysiological Testing for Assessing Construction Workers' Task Performance at Virtual Height. *Autom. Constr.* **2020**, *113*, 103143. [CrossRef]
64. Habibnezhad, M.; Shayesteh, S.; Jebelli, H.; Puckett, J.; Stentz, T. Comparison of Ironworker's Fall Risk Assessment Systems Using an Immersive Biofeedback Simulator. *Autom. Constr.* **2021**, *122*, 103471. [CrossRef]
65. Tixier, A.J.-P.; Hallowell, M.R.; Albert, A.; van Boven, L.; Kleiner, B.M. Psychological Antecedents of Risk-Taking Behavior in Construction. *J. Constr. Eng. Manag.* **2014**, *140*, 04014052. [CrossRef]
66. Sacks, R.; Perlman, A.; Barak, R. Construction Safety Training Using Immersive Virtual Reality. *Constr. Manag. Econ.* **2013**, *31*, 1005–1017. [CrossRef]
67. Nykänen, M.; Puro, V.; Tiikkaja, M.; Kannisto, H.; Lantto, E.; Simpura, F.; Uusitalo, J.; Lukander, K.; Räsänen, T.; Heikkilä, T.; et al. Implementing and Evaluating Novel Safety Training Methods for Construction Sector Workers: Results of a Randomized Controlled Trial. *J. Saf. Res.* **2020**, *75*, 205–221. [CrossRef]
68. Zhao, D.; McCoy, A.; Kleiner, B.; Feng, Y. Integrating Safety Culture into OSH Risk Mitigation: A Pilot Study on the Electrical Safety. *J. Civ. Eng. Manag.* **2016**, *22*, 800–807. [CrossRef]
69. Raimbaud, P.; Lou, R.; Danglade, F.; Figueroa, P.; Hernandez, J.T.; Merienne, F. A Task-Centred Methodology to Evaluate the Design of Virtual Reality User Interactions: A Case Study on Hazard Identification. *Buildings* **2021**, *11*, 277. [CrossRef]
70. Lu, X.; Davis, S. Priming Effects on Safety Decisions in a Virtual Construction Simulator. *Eng. Constr. Archit. Manag.* **2018**, *25*, 273–294. [CrossRef]
71. Song, H.; Kim, T.; Kim, J.; Ahn, D.; Kang, Y. Effectiveness of VR Crane Training with Head-Mounted Display: Double Mediation of Presence and Perceived Usefulness. *Autom. Constr.* **2021**, *122*, 103506. [CrossRef]
72. Joshi, S.; Hamilton, M.; Warren, R.; Faucett, D.; Tian, W.; Wang, Y.; Ma, J. Implementing Virtual Reality Technology for Safety Training in the Precast/Prestressed Concrete Industry. *Appl. Ergon.* **2021**, *90*, 103286. [CrossRef] [PubMed]
73. 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*, 04014024. [CrossRef]
74. Shi, Y.; Du, J.; Ahn, C.R.; Ragan, E. Impact Assessment of Reinforced Learning Methods on Construction Workers' Fall Risk Behavior Using Virtual Reality. *Autom. Constr.* **2019**, *104*, 197–214. [CrossRef]
75. Atherinis, D.; Bakowski, B.; Velcek, M.; Moon, S. Developing and Laboratory Testing a Smart System for Automated Falsework Inspection in Construction. *J. Constr. Eng. Manag.* **2018**, *144*, 04017119. [CrossRef]
76. 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*, 04015030. [CrossRef]
77. Fenais, A.; Ariaratnam, S.T.; Ayer, S.K.; Smilovsky, N. Integrating Geographic Information Systems and Augmented Reality for Mapping Underground Utilities. *Infrastructures* **2019**, *4*, 60. [CrossRef]
78. Talmaki, S.; Kamat, V.R. Real-Time Hybrid Virtuality for Prevention of Excavation Related Utility Strikes. *J. Comput. Civ. Eng.* **2014**, *28*, 04014001. [CrossRef]
79. Dong, S.; Li, H.; Yin, Q. Building Information Modeling in Combination with Real Time Location Systems and Sensors for Safety Performance Enhancement. *Saf. Sci.* **2018**, *102*, 226–237. [CrossRef]
80. Cheng, T.; Teizer, J. Real-Time Resource Location Data Collection and Visualization Technology for Construction Safety and Activity Monitoring Applications. *Autom. Constr.* **2013**, *34*, 3–15. [CrossRef]