BIM data flow architecture with AR/VR technologies: Use cases in architecture, engineering and construction

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ABSTRACT

The construction of a building comprises several phases and involves many stakeholders. As projects have become more and more complex, the Building Information Modeling (BIM) methodology was proposed to unify projects around a Digital Twin of the information necessary for collaboration. In recent years, Augmented Reality (AR) and Virtual Reality (VR) have shown their relevance in assisting in various construction activities. However, their use requires additional refinement for them to be integrated into the BIM process. This literature review is an analysis of the cutting-edge applications of AR and VR in Architecture Engineering Construction (AEC) projects and prevailing trends in their usage. This review focuses on publications related to BIM's safety applications (such as risk prevention and site operations during construction phase), as well as on data flow architectures between BIM and AR or VR applications.

Keywords

- Architecture Engineering Construction (AEC)
- Data flow architecture
- Building Information Modeling (BIM)
- Augmented Reality (AR)
- Virtual Reality (VR)
- Systematic Literature Review (SLR)

1 INTRODUCTION

1.1 Context

The Architecture Engineering Construction and Facility Management (AEC/FM) industry is constantly looking for innovations, new methods and tools to improve workflows in building or infrastructure construction and maintenance projects. Optimizing workflow is a significant challenge because there are many stakeholders and multiple forms of knowledge involved. Over several decades, IT has revolutionized the industry and has enabled improved collaboration, productivity and construction quality [1].

A construction project comprises several phases. First, there is the design phase. In this phase a building is conceived in three dimensions by a dedicated team, visualizing and collaborating on the project and performing defect management in order to identify solutions before construction begins [2]. The design phase also includes simulations and studies relating to structural integrity, light conditions and potential future weather impacts on the building [3]. The second and most complex phase is the construction phase. It involves many worksite workers but also workers in engineering and design offices. A construction site is dynamic and subject to many hazards that can compromise the project timeline, the quality of the construction and the safety of those who work there [4]. Finally, the post-construction phase is the longest phase in the life cycle of a building and lasts about 30 years. Maintenance operations are carried out as part of FM activities, "to provide a comfortable living and working environment as well as to upkeep equipment to prevent functional failures" [5].

Building Information Modelling (BIM) is a process for collaborative project management using a 3D model of the work that is updated and populated with metadata throughout the construction project. It allows a construction project to be followed through all the phases described above. The use of BIM is currently neither systematic nor used globally for construction projects. There are common issues that often prevent the implementation of BIM, including work practice (internal expertise level of BIM knowledge) and process issues (BIM authoring), technical issues (BIM versioning) and other issues (misinformation of what IM is and how to implement it into the current work practice) [6]. However, advanced computer technology allows the digital model and associated knowledge to be accessed and manipulated on worksites. Mobile devices such as smartphones or tablets can be turned into tools to help work sequence planning, to monitor differences between versions "as planned" and "as built", to visualize the 3D geometry of any component, or to consult information on the construction process. New technologies such as Augmented Reality (AR) and Virtual Reality (VR) are increasingly used in construction projects to enhance preventative safety, productivity and quality [7], [8], [9]. The utilization of these technologies in the AEC sector and their innovative use and integration into BIM prompt several research questions. Through a Systematic Literature Review (SLR), this research focuses on these questions and trends in the use of AR and VR [10]. Section 1.2 firstly assesses previous literature reviews related to the AR and VR usage in the AEC industry.

1.2 Past Literature Reviews related to the subject

This study of existing literature reviews of AR or VR and BIM in AEC projects assesses the value of the contribution that an original Systematic Literature Review (SLR) makes to the field. Ten literature reviews were identified and compared in the following table (table 1):

Research paper	Period	Research approach	AEC phase	Technologies	BIM?	Specific focus	Result
[11]	1999 – 2012	5 steps: A. Journals and articles selection B. Review C. Categories definition D. Classification E. Discussion	Construction	AR	No	On-site construction monitoring	The future trend would be the use of AR mobile web-based systems
[12]	1997 - 2018	Identifying relevant publications in distributed sources and scientific databases using keywords.	All	AR and VR	No	Construction project management	AR and VR are beneficial to management in the AEC industry facilitating better communication, visualization, quality and reducing project time.
[13]	2015	Phone interviews with safety professionals, safety training providers and nationally authorized training centers.	Construction	VR	No	Construction safety applications	The authors assess Virtual Reality Environment web-based tools positively in its ability to facilitate distance collaborations.
[14]	2000 - 2017	Content analysis review	Construction	AR	No	On-site	A summary of achievements and challenges in AR/VR for construction safety is presented.
[15]	2013 - 2018	Studying case studies from other research papers	Design	AR and VR	Yes	Hospital construction projects	Significant cost reduction using BIM with AR/VR
[16]	2013 – 2018	Identifying relevant publications in distributed sources and scientific databases using keywords.	Design and Construction	AR	Yes	Lean process	A need of more research to improve and easily use AR in BIM
[17]	2000 - 2015	N/A	Construction	VR	No	Construction Occupational Safety and Health Training	The authors recommend pursuing the study using simple, affordable and low-cost VR hardware.
[18]	1997 - 2017	Identifying relevant publications in distributed sources and scientific databases using keywords.	All	VR	Yes	Education and training in construction engineering	The authors categorize VR applications into 4 groups and observe an evolution of VR technology over-time.
[19]	2008 - 2019	Critical review of the two subjects, AR and BIM, separately.	All	AR	Yes	Evolution of research trends	Four AR developing technologies are presented.
[20]	2013 - 2018	SLR	All	VR	Yes	Research trends	A three-layer system architecture is commonly used for BIM based VR applications

Table 1 - Comparative table of past literature reviews

Although several use cases are defined in these past literature reviews, there is a lack of research focused on software architectures that facilitate the use of AR and VR in BIM at the construction phase. This review addresses this in adequacy. The review provides perspective on state-of-the-art applications of AR and VR in AEC projects, a detailed analysis of their usage in the construction, design and maintenance phases. Applications related to risk prevention activity, training and safety operations on site during the construction phase are also discussed. Furthermore, the different data flow systems used to communicate between BIM models and AR or VR technologies are assessed. Finally, the challenges of integrating AR and VR into BIM for these applications are discussed. The SLR covers publications from 2010 to 2020, and the methodology is described in section 2.

2 SYSTEMATIC LITERATURE REVIEW METHODOLOGY

2.1 Method

The methodology applied in this study was based on the SLR procedures proposed and adopted by [10][21][22]. Relevant publications were identified in distributed sources and scientific databases using keywords, inclusion criteria and exclusion criteria. However, intermediate phases have been added in iterations as too many articles remained before the last phase and more articles needed to be excluded. The phase iterations and results process are shown in figure 1 and the details are explained below.

2.2 Research questions and search query

To define the SLR scope of interest, the following research questions were addressed:

- Q1: What is the state-of-the-art of AR and VR applications in AEC projects?
- Q2: What are the research trends and use cases using AR and VR in the construction phase?
- Q3: What are the main methodologies applied or software architectures used to communicate between BIM and AR, or VR, and what are the challenges associated with each of them?

To collect the most relevant publications for the study, different keywords were used on different scientific databases including Google Scholar, Scopus, Web of Science. Finally, Publish or Perish[1] software was used to gather publications with abstracts in a .lib file. The first filters applied to the search were the absence of patents and a publication date between 2010 and 2020. The SLR focused on publications more recent than 2010 because AR, VR and BIM technologies are evolving quickly. The following search query was most effective on Publish or Perish and yielded us 1090 publications: *allintitle:("Building" OR "Construction" OR "BIM") ("augmented reality" OR "virtual reality" OR "AR" OR "VR").*

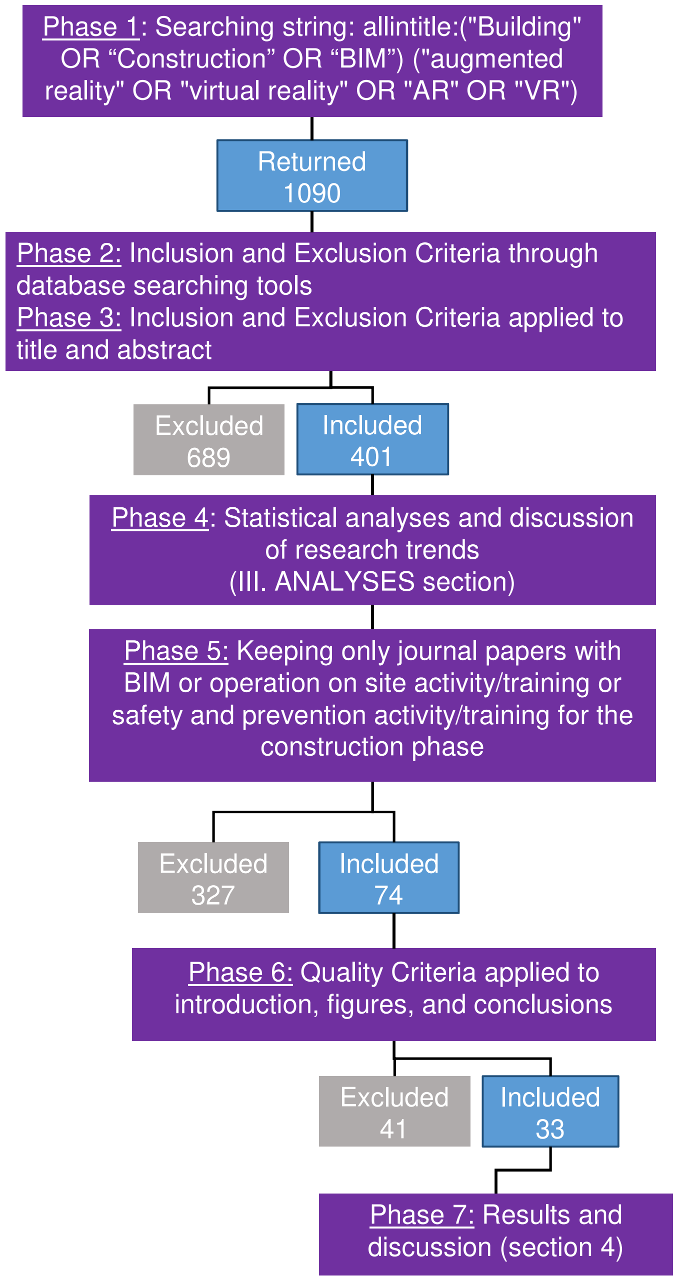


Figure 1: Systematic Literature Review results by phase iterations

[1] https://harzing.com/resources/publish-or-perish

2.3 Inclusion and Exclusion Criteria

After gathering 1090 articles on the database, Inclusion Criteria (IC) and Exclusion Criteria (EC) were applied in the first and second phases by searching the title and the abstract of each publication.

The following IC were defined:

- IC1: a primary study that assesses the use of AR or VR in building construction and maintenance.
- IC2: a primary study that assesses state-of-the-art AR, VR or BIM technology.

The following EC were defined:

- EC1: the language is not English
- EC2: the field is not engineering, nor related to computer science.
- EC3: the study is not construction related nor building maintenance related

In the first phase, the IC and EC were used in database search tools and 823 articles remained. In the second phase the collected data was refined manually by comparing the IC and EC to the titles and abstracts of the publications yielding 401 articles. These articles were used to create a global analysis about construction phases, the use of AR/VR technologies and their categories of usage in construction. The analyses are detailed in section 3 Global trend analysis of AR/VR technology usage in the AEC/FM industry.

2.4 Intermediate Steps

Additional data for the analyses were sought out by classifying the collection of articles by their field application, use cases, and technology usage.

This intermediate phase retained journal publications related to BIM, and safety applications such as preventative measures and training for worksite operations during the construction phase. This yielded 74 articles.

2.5 Quality Criteria

The 74 articles were evaluated to enhance the retrieval of data for the synthesis and analysis of results. The introductions, figures and conclusions of articles were assessed and scored up to 4 in terms of the following Quality Criteria (QC):

- QC1: the technologies are not obsolete
- QC2: the methodology applied to the data workflow is well explained, detailed, innovative
- QC3: the case studies are well detailed and applicable
- QC4: the metadata BIM are present, modifiable and reusable.

For each QC, a score of 0, 0.5 or 1 was assigned. Only articles scoring a total higher or equal to 2 were kept in this final phase, which resulted in 33 publications. The discussion related to these selected articles is presented in section 4 Focused analysis of AR/VR technology usage in the construction phase.

3 GLOBAL TREND ANALYSIS OF AR/VR TECHNOLOGY USAGE IN THE AEC/FM INDUSTRY

The primary research aim of this study was to assess the state-of-the-art applications of AR and VR in construction projects. This assessment was made from the 401 publications remaining after the Phase 2 of the SLR.

813 different keywords were associated with these publications, with 1617 total occurrences. The keywords that appeared the most frequently in decreasing order of frequency were “virtual reality”, “augmented reality”, “BIM”, “construction”, “construction safety”, “construction management”, “simulation,” “construction industry”, “visualization”, “architecture” and “facility management.” The first four keywords were expected as they relate to the search query made in the scientific database. The keyword “construction safety” was also understandable because safety and risk prevention are priorities for construction companies worldwide to keep their workers safe [23]. The keyword “construction management” encompasses management of work on site for planning, controlling or executing tasks, as stated in [24]. The detailed analysis was composed of three subsections: the AR/VR technology found in the literature review, their usage in case studies and finally their integration with BIM.

As described in the introduction and explained by [11], [16], and [25], research and development on "Building" or "Construction" associated with AR or VR technologies can be divided into the following three phases: (1) Design, (2) Construction, and (3) Facility Management (FM). The distribution of research papers on AEC phases from 2010 to 2020 is presented in Table 2 here below. A publication could be counted several times if multiple AEC phases were studied in it. In total, there were 290 publications on construction phase [26][27][28] with a peak in frequency in 2019. There were 82 publications on design phase [29][30] with a peak in frequency in 2017 and there were 75 on FM phase [31][32][33] with a peak in frequency in 2019.

Most of the papers dealt with the design and construction phases. These articles largely treated data exchange and collaboration around design or construction management with AR or VR [34][35][36]. The second most numerous publications combining multiple phases studied all three phases. The majority of these articles dealt with literature reviews [11][37][38]. Finally, the third most numerous publications combined construction and FM phases. These articles mostly related to project collaboration and building delivery in VR [39][40][41]. Finally, only one article studied the design and FM phases and proposed combining workflows to access BIM in VR [42].

Year			***AEC Phase***				***Technology***	
***	Design	Design/Construction	Construction	Construction/FM	FM	All	AR	VR
2010	1	1	8	1	3	0	2	8
2011	2	0	14	2	3	0	7	11
2012	4	0	22	0	6	2	18	12
2013	5	1	39	1	8	4	26	17
2014	2	0	19	2	9	0	18	8
2015	6	2	23	0	4	0	19	15
2016	7	3	22	0	4	1	13	15
2017	20	3	29	0	7	5	25	23
2018	16	1	47	2	10	2	31	42
2019	16	6	62	2	17	1	43	46
2020	3	1	5	0	4	0	7	5
Total	82	19	290	13	75	15	209	202

Table 2 – Number of articles covering AEC phases and technologies annually from 2010 to 2020

A sudden increase in studies on the design phase took place in 2017, unlike the construction and FM phases that saw gradual increases over time. These two phases have more related research in studies because they are more complex. The constant data updates and conflict management involved in the design and construction phases result in greater complexity in terms of workflow usage, technical architecture and interoperability. Therefore, there are more technical problems to solve. Moreover, the technological advancements in AR and VR over time are also linked to these results that will be elaborated upon in the following sections.

3.1 AR/VR Technology Found in the Literature for AEC Projects

In table 2, the numbers of publications studying augmented and virtual reality technologies are almost equal. However, a publication could be counted multiple times in the tables if it analyzes both AR and VR technologies. 30 publications fall into this category and most are literature reviews or check which technology is the most suitable for a construction project [43][44][45]. The literature showed that between AR and VR technologies there were common developmental paths like 3D scene authoring and common functionalities like data consultation or color-coding elements. However, there were also unique features such as full-scale outdoor visualization for AR software and immersive simulation tools for VR software [43]. In [44], feedback from students revealed that they prefer immersive devices to 360° panoramic photography. Moreover, they claimed that using VR for construction site visits instead of being physically on site was a positive experience.

Virtual Reality

Further research was undertaken by classifying the devices used according to their characteristics. VR is based on a set of technologies that immerses a person in a digital simulation of the real world or in an imaginary world. It is a simulation where the user is invited to interact in three dimensions with a computer-generated environment. The four categories of VR devices are shown in table 3. The first two categories are:

- “3D KMS” - For many years in the literature, the scenes have been primarily visual with imagery displayed on a computer screen. These devices were referred to as “3D KMS” (Keyboard Mouse Screen) devices or "desktop-based VR" as defined by [18] and comprise simple interaction with a keyboard and a mouse through the PC interface [3].

- "VR CAVE" - Another category of VR devices which were classified as "VR CAVE" devices, There are solutions such as a Powerwall, which is large-screen projected and offers an immersive environment with a wide range of views and multi-users collaboration possibilities [46], or a CAVE which is an immersive multi-screen cube in which it is easy to experience VR alone or in groups [47].

More recently in the literature, VR experiences are mediated through a head mounted display (HMD), consisting of a display screen on each eye. These are classified in two different categories:

- "VR Standalone" - VR Standalone devices refer to headsets with built-in screens, processors, and storage. These are also called all-in-one headsets such as Google Daydream, Samsung GearVR or Oculus Go (which was discontinued and replaced by the Oculus Quest, released in 2020) [48]. VR Standalone also includes headsets made of a combination of mobile phone and mounting structure like Google Cardboard, first released in 2014 [49].
- "VR tethered HMD" - These are modern VR devices that are wired to a computer. Popular VR HMDs include the HTC Vive Cosmos, Oculus Rift, Samsung Gear VR and the PlayStation VR.

Device category	***3D Keyboard Mouse Screen (KMS)***	***VR CAVE***		***VR Standalone HMD***		***VR Tethered HMD***	
Subcategory	Not immersive	Powerwall	CAVE	Low cost	All-in-one	Outside in	Inside out
Commercial examples							
Price	++	+++	++++	+	++	++	++
Interaction	+++	+	++	-	++	+++	+++
Tracking	N/E	Outside in	Outside in	IMU	Inside out	Outside in	Inside out
Portability	+++	+	-	+++	+++	+	++
Configuration Setup	Instantaneous	Start projectors (5-10 min)	Start projectors (2 min)	instantaneous	Room setup (5min)	Install tracking camera + Room setup (15-30 min)	Room setup (5 min)
Requires external computing power	Is itself a computer	1 PC	Cluster of PCs	No	No	1 PC	1 PC
Geometry optimization needed	No optimization needed	Optimization needed	No optimization needed	Optimization needed very much	Optimization needed	No optimization needed	No optimization needed
Usage	Virtual visit, simulations, virtual meetups, pseudo-3D interaction in scene, text commentary	Virtual visit, simulations, virtual meetups, 3D interaction in scene, multi-user experience	Virtual visit, simulations, virtual meetups, 3D interaction in scene, multi-user experience	Virtual visit, simulations	Virtual visit, simulations, virtual meetups, 3D interaction in scene	Virtual visit, simulations, virtual meetups, 3D interaction in scene	Virtual visit, simulations, virtual meetups, 3D interaction in scene

Table 3 - Comparison of VR devices

Table 3 shows the variety of devices covered in the literature. Main usages were identified according to the device. VR tethered HMD devices allow 3D interactions and do not need optimized 3D models because rendering is performed by a powerful GPU card. Therefore, these devices are mainly used to review designs or in construction management because they require importing regularly the most recent BIM model which is computationally intensive when used in VR [50]. All-in-one VR standalone HMDs need optimized 3D models because they have low computational power. However, standalone HMDs are mobile devices that can be setup in only a few minutes and therefore are most frequently used for long-term usage applications such as training. Low-cost HMDs are only used for visualization or virtual visits because interactions are limited. VR CAVE devices are applicable for multi-user meetings and are often used for design reviews. Finally, 3D KMS devices allow users to interact with the 3D environment without a dedicated device. Although the 3D interactions are limited, 3D KMS devices are useful for writing textual feedback which is more difficult to do with HMD controllers [51].

Augmented Reality

AR overlays 3D virtual content onto the real world. The user therefore predominantly sees the real world. Virtual objects provide relevant and contextualized information. An AR marker-based system is the simplest way to do AR, which uses real world patterns or any visual markers. Vuforia from PTC was first released in 2012 and is an AR framework which integrates multiple tracking algorithms [54]. AR marker systems can be performed by image-, object-or face tracking [53]. This tracking technology assumes that there is an identified and trackable object in the scene. Another way augmented reality is performed uses simultaneous localization and mapping (SLAM) algorithms [54]. This kind of tracking does not look for a known object in the real scene but builds an internal 3D representation of the scene and places virtual objects accordingly. Modern AR engines like Google ARCore or Apple ARKit, (released in 2017) and Microsoft HoloLens released in 2016 use AR SLAM-based systems [55]. Vuforia similarly released an AR SLAM-based technology [56]. There are three categories of AR devices that are detailed in table 4:

- “AR mobile handheld” - publications using smartphones or tablets with AR marker-based or AR SLAM-based solutions were classified as “AR mobile handheld” devices [57].

- “AR mobile smart glasses” - publications using Google Glasses, Microsoft HoloLens or HMD on optical see-through mode were classified as “AR mobile smart glasses” devices [55].

- “AR fixed” - systems setup with a fixed camera which streams the real world to a monitor with the additional virtual elements were classified as “AR fixed” devices [58].

Device category	***AR mobile handheld***	***AR mobile smart glasses***		***AR fixed***
Subcategory	Smartphone or Tablet	Optical See-Through (OST)	Optical Glance	A camera and pc screen
Commercial examples				
Price	++	+++	++	+++
Interaction	++	+	+	-
Tracking	Marker-based and SLAM-based	Marker-based and SLAM-based	Marker-based and SLAM-based	Mainly Marker-based
Portability	++	+++	+++	-
Needs external computing power	no	no	Embedded small PC unit	Is a PC
Application optimization needed	Optimization needed	String optimization needed	String optimization needed	No optimization needed
Usage	Superimpositions on top of physical world, simulations, 3D projections on markers	Superimposition on top of physical world, simulations, 3D projections on markers	Superimposition in front of user view, 3D projections on markers	Superimposition on top of PC screen

Table 4 - Comparison of AR devices

Table 5 shows the distribution of AR and VR devices in publications for each AEC Phase. VR tethered headsets are the most frequently used devices as they are more affordable than CAVE technology [59] and more practical than Google-Carboard and equivalent technology [48]. However, the release of all-in-one 6DOF (Degree Of Freedom) headsets (such headsets include the Oculus Quest released in 2019) may change this distribution even if they require optimized 3D models.

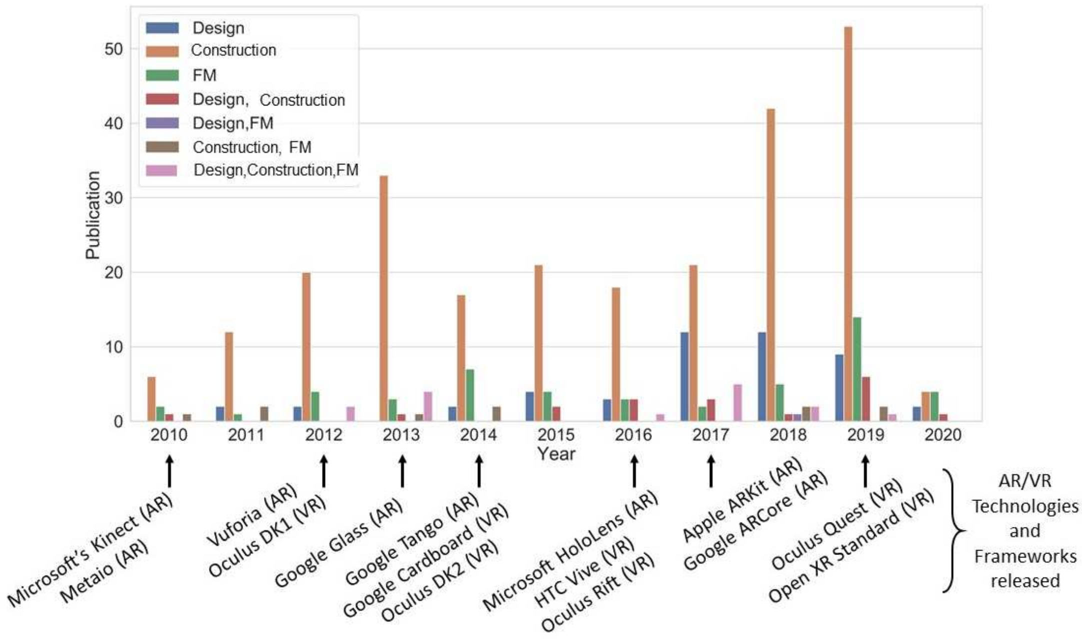


Figure 2: Publication frequency against AR and VR technologies and AEC phases, measured annually from 2010 to 2020

Table 5 - AR and VR device distribution by construction phase

Figure 2 shows the evolution of AR and VR technologies and frameworks in construction phases in the literature from 2010 to 2020. In 2017 20 publications have been released on the design phase, of which 51% used AR technology and 49% used VR technology. This could be explained by the release of AR and VR hardware in 2016, including the Microsoft HoloLens [60], the Oculus Rift [61] and the HTC Vive [62] presented in figure 2. The literature reveals that within the design phase, the VR technology is predominantly used to preview the design of the building.
The first peak in publications on VR in the construction phase can be observed in 2013 with 39 publications released. This can be explained by the release of AR frameworks such as Vuforia [63] and the hardware Oculus DK1 for VR applications [8]. More than 60% were publications using VR technologies such as the CAVE, VR tethered HMDs or the simple Key-Mouse-PC Screen for simulation and coordination [46][66]. A second peak appears in 2018 followed by a higher one in 2019 where equal use of AR and VR technology research was published. Improvements of VR tethered HMD devices and easier integration and development tools resulted in an increase in studies of design review and collaborative platforms [65]. Access to better AR technologies such as Apple ARKit and Google ARCore available on tablets and smartphones also explains the increase in research. These devices no longer require markers and this has made systems easier to use on worksites where construction has not begun [66]. The AR devices that are used most in the construction phase are AR mobile handheld devices, as shown in table 5.

In 2012, 2013 and 2014 a major increase of publications using VR in the FM phase can be seen in table 2. The Metaio and Vuforia frameworks were used for building inspections and operation instructions in AR (using AR markers or SLAM-based systems as the building already exists). Exit signs, for example, have great potential to act as natural markers as proposed by [5]. As shown in table 5, AR mobile handheld devices are predominantly used in FM phase research. This is confirmed by the peak in 2019 where FM phase research implemented Apple ARKit and Google ARCore, which have great potential to help operators build maintenance operations [67].

Summary of Findings

Concerning the type of devices available in literature and their usage, the dominant tendencies are:

- VR tethered HMD and VR CAVE allow 3D interactions and do not need optimized 3D models because rendering is performed by a powerful GPU card. These devices are mainly used for design reviews or construction management as these activities require regularly updated BIM data [50].
- VR standalone HMD devices require optimized 3D models because they have low computational power. They are predominantly used for long-term applications, such as training.
- The launch of AR SLAM-based solutions to the market has sparked new studies in the construction phase because AR marker-based solutions did not prove effective on worksites due to the inconvenience of keeping markers in such environments. AR SLAM-based solutions are easier to use but the tracking is not accurate enough while rendering 3D on top of the physical world.

3.2 Usage of AR and VR Technology in the AEC Phases

This section presents activities and trainings found in the SLR within AEC phases and the technologies used. The study divides the data into two categories:

- Activities supported by AR/VR technology. These are specific tasks performed in each AEC phase and are represented in the Activities rows of table 6. For example, the activity of quality control is a construction process performed by a construction company in which the company checks for defects in work performed [68].
- Trainings supported by AR/VR technology. These are the learning tasks related to an activity [69] and are represented in the Trainings rows of the table below.

An activities and trainings article may be counted several times if it involves different AEC phases in a single publication and might also not be counted if no technology was identified, because the data was generated by applying IC and EC to titles and abstracts.

		Articles	***AEC Phase***								
	***	***	Design			Construction			FM		
	***	***	Technology		Articles	Technology		Articles	Technology		Articles
	***	***	AR	VR	***	AR	VR	***	AR	VR	***
Activities	*Design review*	**79**	10	17	25	19	31	45	5	6	9
	Construction management	**70**	5	3	6	37	25	57	4	5	7
	Maintenance	**52**	3	2	4	5	7	10	31	9	38
	Simulation	**28**	1	10	11	1	13	13	0	4	4
	Quality control	**21**	2	1	2	17	3	18	1	0	1
	Logistics	**15**	0	1	1	10	3	13	1	0	1
	On-site operation	**10**	1	0	1	6	2	8	1	0	1
	Safety and risk prevention	**6**	0	1	1	1	2	2	2	2	3
	Sustainable design processes	**4**	0	0	0	1	0	1	2	1	3
	Cost measurement	**3**	0	0	0	2	0	3	0	0	0
Trainings	*Safety training*	**11**	1	0	1	2	7	9	1	0	1
	Construction management training	**8**	1	0	1	3	4	5	1	1	2
	Maintenance training	**6**	1	0	1	1	2	3	1	1	2
	On-site operation training	**5**	1	0	1	2	2	3	1	0	1
	Total	***	26	35	***	107	101	***	51	29	***

Table 6 - Activities and trainings studies by AEC phase and technology

For all AEC phases combined, the top activities found in publications were “design review,” “construction management”, “maintenance”, “simulation”, “quality control” and “logistics.” The activities that were less frequently identified were “on-site operation”, “safety and risk prevention”, “sustainable design processes” and “cost measurement.” Section 3.2.1 will detail each activity and training and will explain why some activities are well represented in literature while others are not.

3.2.1 Activities

The dominant activity in the literature of the design phase is design review. In design reviews a proposed design solution is analyzed and evaluated according to the requirements and specifications from the program, the user and the owner. The VR solution allows an effective communication solution during review meetings between designers and clients by making the design specifications well understood [70].

In the construction phase, the activity of design review refers to the detection of clashes between structural installations and architecture within the virtual building model [2] (see figure 3 – left). This is the second most common activity found in the construction phase publications. During construction, there are multiple independent subcontractors working on the worksite and successful construction relies on close coordination between all these actors. Issues identified in the 3D model are noticed and addressed by coordinating project members who find solutions. VR technology is the dominant technology used for this activity as presented in table 6. VR technology is often used to visualize, analyze and assess designs in design and construction phases [50]. AR technology is predominantly used to review designs by projecting the 3D view from the 2D drawing [71] (see figure 3 – right).

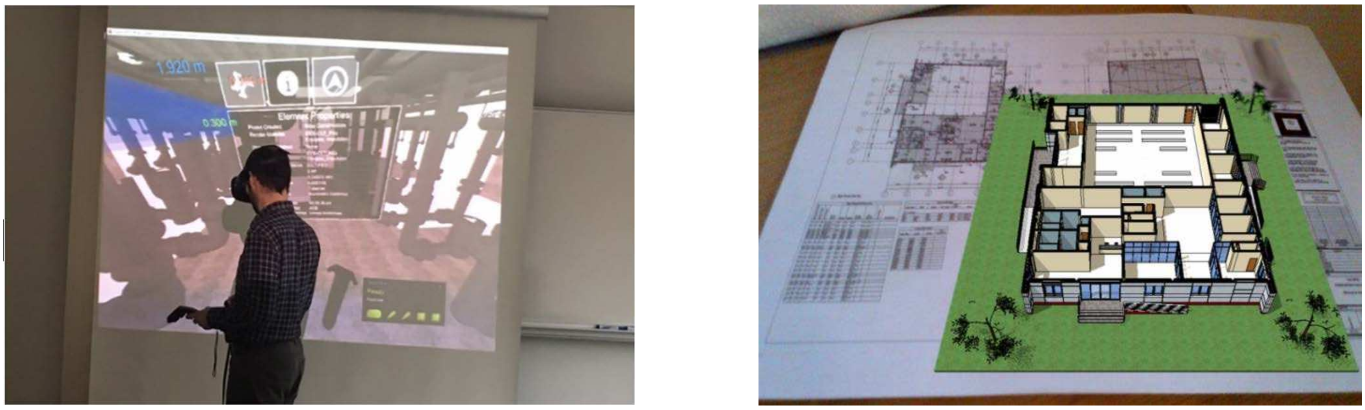


Figure 3: (left) VR tethered HMD used for measuring space between model elements [2], (right) superimposed 3D view off the 2D QR-code enabled drawing using AR mobile handheld [71].

Construction management activities consist in maintaining schedules, helping construction managers and on-site supervisors to remain efficient and making decisions [7]. Construction management is mainly covered in the construction phase literature. In table 6, the papers found for the design and FM phases are literature reviews covering general topics for the three AEC phases. Most of the research in the construction phase used AR technology in their studies. VR technology can be helpful in providing detailed and informative animations of all the phases of the construction. This enables the onsite team to perform or supervise tasks efficiently [72]. VR technology also provides opportunities to simulate processes by making decisions and then watching the real-time results. Decisions made in VR during an hour of experimentation were in higher number than if it was on the field [24].

Among different FM activities, maintenance refers to activities taken to avoid building malfunction such as repairing and replacing [73]. Maintenance is the main activity found for the FM phase literature, with most publications using AR technology. In this application, the AR user is surrounded by information about the facilities. Water pipes under floors and ventilation ducts above ceilings often do not have AR markers as they are hidden from operators. Therefore, a method distinct from AR-marker detection is necessary [73]. AR-SLAM based technology are promising to overcome this limitation. One would expect the activity of maintenance to be found exclusively in the FM phase literature, as it refers to managing asset life cycle and facilities of buildings. However, some design phase and construction phase publications could be found for this activity. This can be explained by the need to plan facility maintenance operations upstream of the FM phase [39].

Simulations using only VR technology were found for the design phase and the construction phase literature. A simulation describes the future behavior of a building in its environment and aids in the adjustment of designs to these complex environmental parameters. For example, in the design phase literature a study analyzed the wind direction on site and simulated its changes [3]. Another study used simulation to visualize realistic lighting and calculated the approximate energy consumption of the building [74] (see figure 4 – left). In the construction phase literature, a study simulated different construction phases to visualize the project over time and onsite [75]. We can assume that with the development of digital twins interfaced in VR these uses in simulation will develop. Indeed, thanks to the digital twin simulation based on real data, workers would be provided information and predicted state or scenario about building to take decision on its design or during construction phases. However, there is still a challenge on making the data go back from AR/VR into the digital twin when the decision is taken.

The activity of quality control (also called defect management) refers to the inspection of construction works. One of the main issues in construction projects which leads to delays in construction schedules and costs exceeding the budget is the unsuccessful control and management of construction defects [78][77]. For example, inspections could lead to the identification of a block-out at the wrong location in a reinforced concrete wall before the concrete has been cast in place [78] (see figure 4 – right). The construction phase literature largely studied AR in this application. The literature shows that AR technology made it possible to visualize the 3D models of part of the building directly on the field in real-time. Moreover, AR enabled data to be displayed on the physical defects [79].

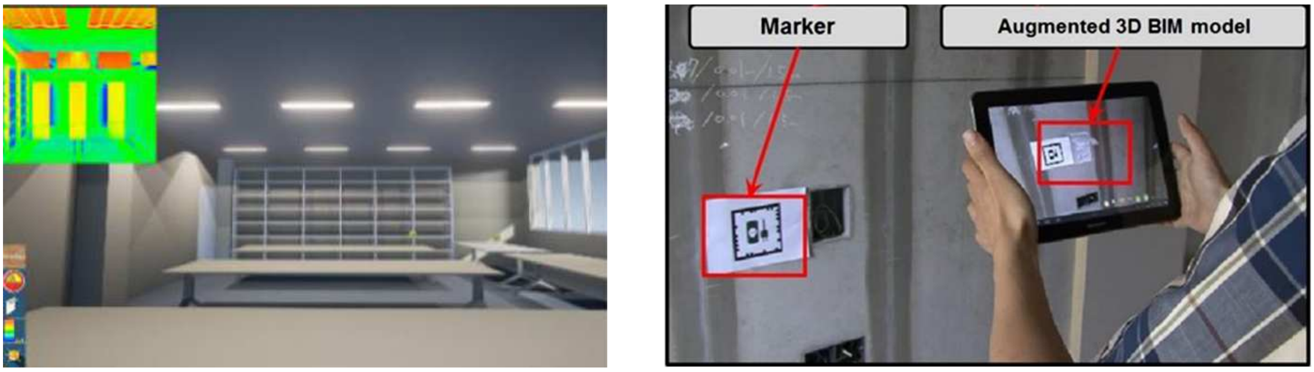


Figure 4: (left) Lighting simulation at daytime using VR standalone [74], (right) AR mobile handheld used on AR site-experiment for quality control [78].

In the construction phase, the site installation plan is defined before the beginning of the construction and material storage is zoned in the worksite space. Additionally, logistics and planning are executed to make sure that scheduling, deliveries and workers are well coordinated during the construction [80]. Each construction project is unique due to its worksite environment and architecture that makes being prepared with extensive and highly detailed plans necessary. Using VR helps workers to avoid making mistakes while selecting materials and objects by providing additional visual labels [81]. VR solutions also helps with faster identification and decision-making that helps logistical processes to flow smoothly. Most of the research used virtual reality technology [82]. However, AR has clear use cases in visualizing the storage areas on-site. This could help site managers with the management of subcontractor material storage during the construction lifecycle [83].

The on-site operations activity is exclusively found in the construction phase literature and AR is primarily investigated in this literature [84][85]. In the literature AR provides managers and workers with step-by-step assistance and follow up on tasks they are responsible for [86].

The construction phase and the FM phase literature covered safety and risk prevention activities [87][88]. An AR system providing resources related to safety work and environment, as well as notifications to improve planning, preparation, and activities to ensure no unsafe actions has been studied [89]. This system conveyed safety knowledge to managers who were responsible for planning safe facilities and for overseeing workers' safety.

Literature from all AEC phases covered the "sustainable design" activity [90], and used VR as a tooltip helping with visualization [91] (see figure 5 – left). The use of VR was associated with the optimization of energy consumption and the sustainability of the building and its environment [92].

The activity of cost measurement was found exclusively in the construction phase literature and consisted of linking costs with scheduled activities [93] (see figure 5 – right). The study used AR "to obtain the as-built status by superimposing a 3D model over the worksite scenario". VR could allow the inclusion of the client into the cost measurement and design process. By simulating the client's design choices in VR, the bill of quantities could be automatically updated, providing more accurate information on the real cost of the project [94].

Figure 5: (left) 3D KMS for virtual rendering of greening on building's roofs [91], (right) a tag note assigned to a delayed wall using AR mobile handheld [93].

3.2.2 Trainings

Without safety training, construction workers would not be prepared for risky situations on-site [95]. Therefore, this research proposed to investigate training workers in VR where dangerous scenarios can be situated risk free. The importance of this training is conveyed in table 6 where the literature was largely from the construction phase.

Research on VR training was found in the literature, but in small amounts. For construction management training purposes, a study proposed to use the Second Life VR environment for construction students to learn through simulated event sequences and resource management [69]. [96] used AR technology to superimpose instructional mechanisms on a jobsite which would help the learners to visualize context and spatiotemporal constraints, but also to identify hidden processes (see figure 6).

Figure 6: Superimposed 3D BIM model over worksite construction progress documentation using AR mobile handheld [96].

VR and 3D modelling could bring maintenance training to engineering education and to professional activities as virtual models can be examined with all their related metadata as well as their technical information [97]. Research papers on this topic in table 6 are uncommon and concern both the construction phase and FM phase.

Learning methods for on-site operation training remain out of date and ineffective [49] (see figure 7 - left). To overcome this lack, Wolf and al. propose an approach using mobile VR with gamification elements for teaching and training experienced and novice workers with individual feedback. In [98], to overcome the lack of engagement and interaction, the author proposes a learning system with an "AR Book" consisting in augmenting objects with relevant information which appear while students interact with the training content in the video (see figure 7 - right).

Figure 7: (left) User's perspective (image overlay) of the VR training application using VR tethered HMD [49], (right) AR Book showing a construction equipment displayed on the marker using AR mobile smart glasses [98].

Summary of findings

Some activities are well represented in the literature such as: logistics, quality control, simulation, maintenance, design review and construction management. These activities mainly require 3D model visualization and simple interactions. On the contrary, activities such as cost measurement, sustainable design processes, safety and risks prevention and on-site operation are less represented in the literature. These are activities that require job-specific knowledge and simulation tools. Implementing such interaction and scenarios in AR or VR requires deeper research to achieve interoperability between technology, knowledge and real-time events. This supports the need of conducting a detailed research of methods existing in the literature to develop these activity and training applications that are being studied in section 4.1 Worksite Operations and Risk Prevention or Safety Studies; then existing systems and frameworks for data and technology interoperability which are studied in section 4.2 Data Workflow between BIM and AR/VR Technology.

Concerning training in activities, the review shows that there are fewer activities represented because training in AR or VR also requires complex scenario authoring and interaction development. Safety training is well represented in this study compared to the other trainings because it is a sensitive subject that carries high risk and liability. Improving safety training has been highlighted as a key component in lowering the construction industry's accident rate. Virtual environment-based simulations offer the possibility to gain experience in hazardous situations where failing is not harmful to the learner [13].

Some research papers studied, developed, or proposed frameworks that would fit training as well as activity. [99] explained that "training operators by the means of AR is a consequent continuation of simulations done in VR" and the use of simulations before maintenance missions are showing viable results. Furthermore, the implemented solutions in existing VR training can be adopted and developed in on-site activity where operators face the physical constraints of the jobsite. The same jobsite knowledge can be found in the training for a student to handle a task as for an operator that would follow a step-by-step guide on a given task.

3.3 BIM Process and AR/VR technology integration

After identifying the different construction project activities and training involving AR/VR integration, this research examines projects that are integrated into the BIM process. BIM is becoming the industry standard for construction projects but remains imperfect.

BIM was one of the important areas in VR research in 2010 [6]. According to Gu and al. "BIM is an IT-enabled approach that involves applying and maintaining an integral digital representation of all building information for different phases of the project lifecycle in the form of a data repository" [34]. The benefits of using VR for BIM projects are numerous. It can improve collaboration, planning, data and 3D model visualization for clearer communication among stakeholders and better coordination among all trades leading to better quality project outcomes. AR technology can also be a useful collaborative 3D tool and promises a different way to represent and interact with BIM data into the physical world.

Figure 8 represents the number of publications studying AR/VR in construction projects during the construction phase. Two series are presented, regardless of whether AR/VR data are provided by BIM.

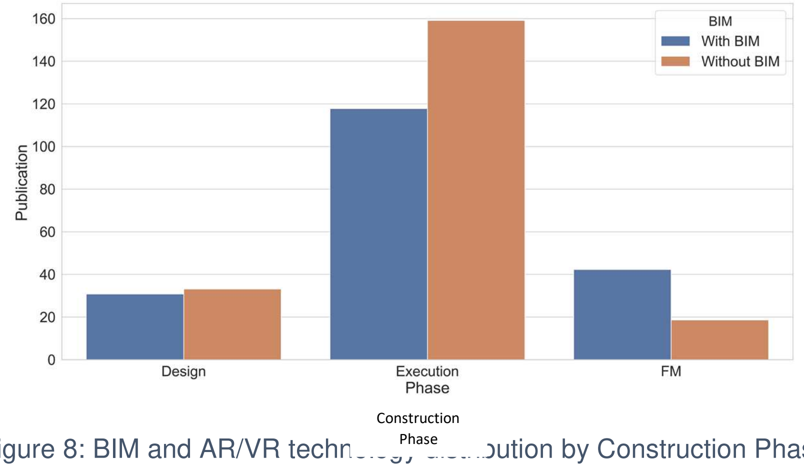


Figure 8: BIM and AR/VR technology distribution by Construction Phase

Across the AEC phases in figure 3 the number of research papers found in the design phase that integrate AR/VR within the BIM process is proportional to the number that do not, fewer research papers found in construction phase integrate AR/VR into the BIM process and finally, most research papers found in the FM phase integrate AR/VR into the BIM process. In the design and construction phases some activities do not require the BIM parametric data to visualize and simulate the 3D Building. However, the FM phase activities usually require BIM data for building operation and maintenance [100].

A BIM dimension is used for solving a specific issue in a construction project process by incorporating extra data to the BIM model [101]. The following BIM dimensions were present in the literature:

- 2D BIM Exchanging Drawings and Papers Through the Project Cycle [102]
- 3D BIM Model Communicating Design Intent with Parametric Data [103]
- 4D BIM Influencing Schedule in case of Construction Project Changes [104]
- 5D BIM Estimating Cost of Construction Project [105]

The following BIM dimensions do not have a stable meaning. There is no consensus as to which BIM activities these dimensions refer to. According to [106], "multiple authors agreed on the consensus of what the BIM 4D and BIM 5D refer to. However, there exists no agreement between the 6D and onwards". As papers of this review are based on 6D or higher BIM, they were still included in this study and were assigned the following definitions:

- 6D BIM Optimizing Energy Consumption & Sustainability [106]
- 7D BIM Managing Asset Life Cycle & Facilities [41]
- 8D BIM Modeling Preventing Accident through Design [107]
- 9D BIM Optimizing Design Management (Lean Construction) [110]

Figure 9 below represents the evolution of BIM dimensions over years, shown through the frequency of studies on the integration of AR/VR technologies into BIM annually from 2010 to 2020, based on 401 papers.

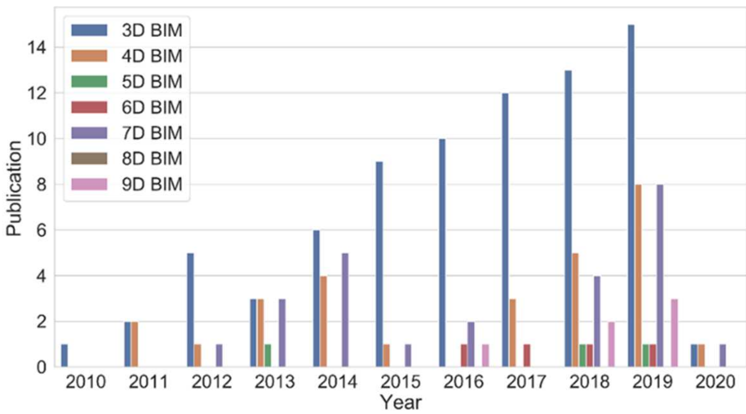


Figure 9: The distribution of AR/VR technology and BIM dimension papers annually from 2010 to 2020

Figure 9 shows a constant upward trend in the frequency of papers on 3D BIM integrated with AR/VR technology. This is because 3D visualizations of parametric data in AR/VR BIM are frequently used in the construction phase. Groups of the AEC industry were interviewed for BIM case studies and these interviews found that visualizing and interacting with BIM models with AR or VR technology enhanced motivation to work and collaborate on BIM project [34].

The 4th BIM dimension has seen increases and decreases in academic interest over the past 10 years. The drop of papers integrating 4D BIM and AR/VR found in 2015-2016 could be explained by the transition of technology. Before 2017 most devices which used AR or VR were VR CAVE [109] [110] [47], AR fixed [111][112] and AR mobile devices [7][113]. After the launch of a new VR headset and AR framework in 2017 publications using AR mobile [114][115][116] and VR HMD devices were found [104] [65].

The 5th and 6th dimensions of BIM associated to AR or VR technologies are almost not explored in the literature. The 5th BIM dimension facilitates cost measurement such as producing bills of quantities. The decline in use of bills of quantities with traditional methods is significant [96]. The reasons for this relate to its complexity, the time intensity of generating them and the use of information retrieved from planning. The same is true of the 6th dimension of BIM. Doing sustainability work on a building is a long process operated throughout the building lifecycle by dependent iterations leading to benefits in energy efficiency for example [90]. The data collected by repetitive facility management and exterior variables (such as the environmental influence on the building) could help to optimize and improve future construction. Therefore, very few publications considering AR/VR integration with 5D or 6D BIM were found in the literature but this appears to be a future trend and the literature may increase in frequency in coming years.

The 7D BIM dimension is related to building operations and maintenance and appears largely in the FM phase literature. The literature shows that the distribution of 7D BIM papers using AR/VR technology follows the same progression from 2010 to 2020 as the FM phase (see figure 4). This is also visible in figure 3 where most of the publications covering the FM phase use AR/VR integrated into the BIM process.

The literature collected in the SLR did not contain any publications related to the 8th BIM dimension and AR/VR. Preventing accidents with design is a complex task and has only recently emerged as a topic of study. Moreover, it requires specific tools to involve people in VR, to study their behavior and detect what could cause an accident. This could explain why this dimension is understudied within the literature.

Figure 9 shows that the 9th dimension of BIM is seeing an increase in academic interest in its integration with AR/VR technologies. The correlation between BIM, lean construction and AR for the design and construction phases was reviewed within the literature [16]. Very little data could be found on workflow automatization and integration with BIM and VR technologies, even though Lean is increasingly studied with BIM processes in construction projects.

Summary of findings

Increasing research interest is being directed at the 5th to 9th BIM dimensions by comparison to the 3rd and 4th BIM dimensions. This is due to the complexity of the knowledge associated with each dimension, as shown in activities and trainings in section 3.2.

Although integrating AR/VR technologies and BIM in the context of AEC/FM is beneficial for all stakeholders, it is still not easy to use these three technologies together and existing solutions may not be reliable [67]. These complexities stem from the following:

- Developing stable solutions instead of multiplying proof of concepts
- Technical challenges of AR an VR technologies
- The technical challenges of BIM integration
- The existence of multiple specific non-interoperable architectures, frameworks, software and hardware.

There is further research on n dimensions of BIM that have not been explored, even where AR/VR technology could be integrated in the BIM process. These subjects may emerge in the future in 5D BIM, 6D BIM, 8D BIM and 9D BIM.

4 FOCUSED ANALYSIS OF AR/VR TECHNOLOGY USAGE IN THE CONSTRUCTION PHASE

For the purpose of the future research that will develop the potential of AR and VR applications in AEC projects particularly in the construction phase, the current research and use cases using AR and VR in the construction phase were studied in detail. As BIM is essential for all future construction projects, publications related to BIM data workflow and communication between BIM and AR/VR technology were focused on.

4.1 Worksite Operations and Risk Prevention or Safety Studies

The second research question addressed in this study relates to current research and use cases using AR and VR for the construction phase. Within the 33 articles, 11 of them were oriented on current research and use cases. Comparative table 7 is structured as follows:

- The matter column conveys the activity or training studied in the publication
- The process information column conveys the information sources used as a knowledge base for the activity or training
- The technology and display device column conveys the AR or VR technologies utilized in the studies
- The participant column conveys whether participants need supervision of an instructor to complete the activity or training
- The evaluation process refers to the method and number of participants to evaluate the proposed activity or training application
- The usability column indicates the ease with which a user can learn new tasks, whether the error rate was low and whether the general system was adequately ergonomic.

	Research paper	*Matter*	*Process information are from:*	*Technology and Display device*	*Participant needs supervision to complete the activity or training?*	*Evaluation process*	*Usability (+/++/+++)*
Worksite operations	[117]	Wood frame construction assemblies	N/A	VR Smartphone and VR Cardboard	no	(110 pers.) pre/post surveys	+
	[86]	Ceramic tile installation	The Turkish Ministry of Education and INTES (Employers' Union of Construction Industry Employers)	AR smart glasses	no	N/A	+
	[118]	Detail of the longitudinal bars cross section of a corner column	Guidance of a teacher in the field of construction techniques	AR PC	no	(40 pers.) Eye tracking and evaluation with true or false questions and short answer questions	+
	[119]	Wood-frame wall assemblies	Phased in Revit by experts	AR Smartphone, AR smart glasses	no	(28 pers.) Questionnaire, direct observation and result analysis	++
	[120]	Pipe spools assemblies	a two-sided isometric drawing and traditional rework completion processes	AR Tablet	no	(61 pers.) Participants were filmed. The videos were watched and segmented into activities and durations to assess the participants' progress during the experiment.	+++
Safety and risks prevention	[4]	Safety management	N/A	AR PC and smart glasses	N/A	The performance of the system was evaluated using 459 images obtained from a construction site.	+
	[121] [122] [123]	Safety education	Korea Occupational Safety and Health Agency (KOSHA)	VR Tablet	no	(25 pers.) Evaluation through hands-on trials with questionnaires and interviews	++
	[124]	Construction site safety	OSHA (Occupational Safety and Health Administration)	VR Tablet	no	Auto assessing the safety knowledge of the students and submitting a report	++
	[95]	Safety education	Accident types reported in [125] and Israel Institute for Occupational Safety and Hygiene (IIOSH)	VR PC	yes	(66 pers.) 3 individual safety knowledge tests (pre, post and 1 month later); experience questionnaire	+++

Table 7 - Comparative table of publications focused on current research and use cases

In section 3.2, it was observed that activity and training applications can be used for the same purpose. In the following sections, activities and trainings in the research papers presented in table 7 are clustered by topic to focus on the usability of each one. The positive and negative points identified are discussed.

4.1.1 Worksite Operations

The use of VR helps students to visualize the final assembly of a wooden construction by navigating around the building unlike traditional 2D plans and drawings [117] (see figure 10 - left). In the proposed training, it would have been even more effective if the 3D construction was sequenced and interactive in the VR application. This would have facilitated a better understanding of the step-by-step tasks of the assembly.

In on-site AR training for ceramic installation [88] (see figure 10 - right), the step-by-step procedure was implemented. In AR training for steel installation [118], each step of the construction was presented and the operator had autonomy to proceed with his tasks. In both trainings, all steps from the beginning to the end of the operation were modeled, animated and then imported to the 3D engine. The developer had to be guided throughout the training development by an expert or had to find the knowledge by himself. This method makes the training inflexible and uneasy to reuse for other tasks. The time required for modeling, animating and developing may be too long if 100+ worksite operations are developed.

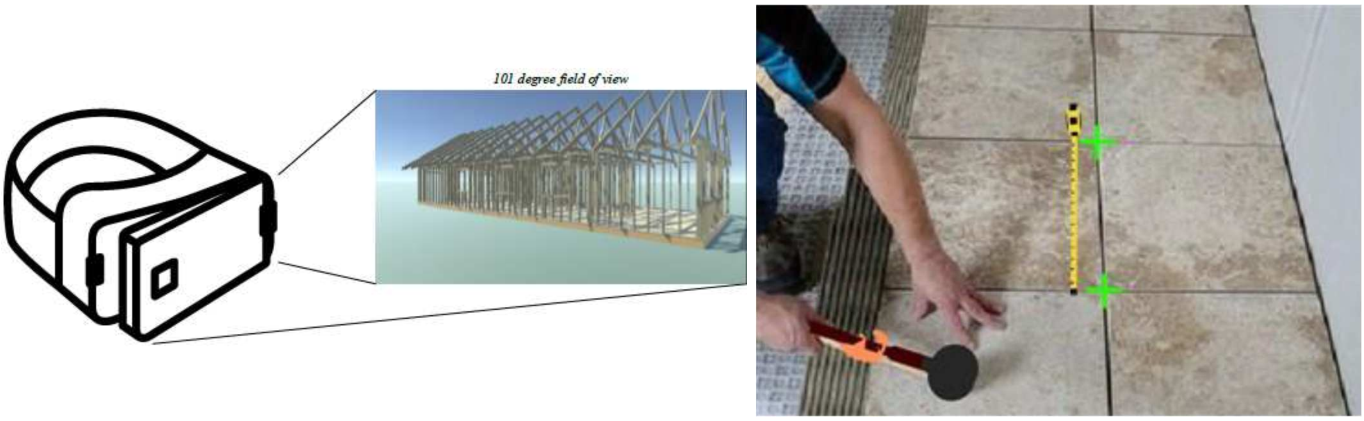


Figure 10: (left) User experience within the VR simulation using a VR tethered HMD [117]; (right) Test of the ceramic tile installation's system using AR mobile smart glasses [86].

To address the support needed by the developer, one study developed an AR application to assist with assembly of construction elements where each step of the assembly was defined in a different phase within the BIM element (see figure 11 - top). The BIM element was sequenced in the BIM software by the assembly expert [119]. Once imported into the 3D engine the developer would retrieve the phases directly from the BIM element to make the operation assistant AR application without needing any further guidance (figure 11 - bottom).

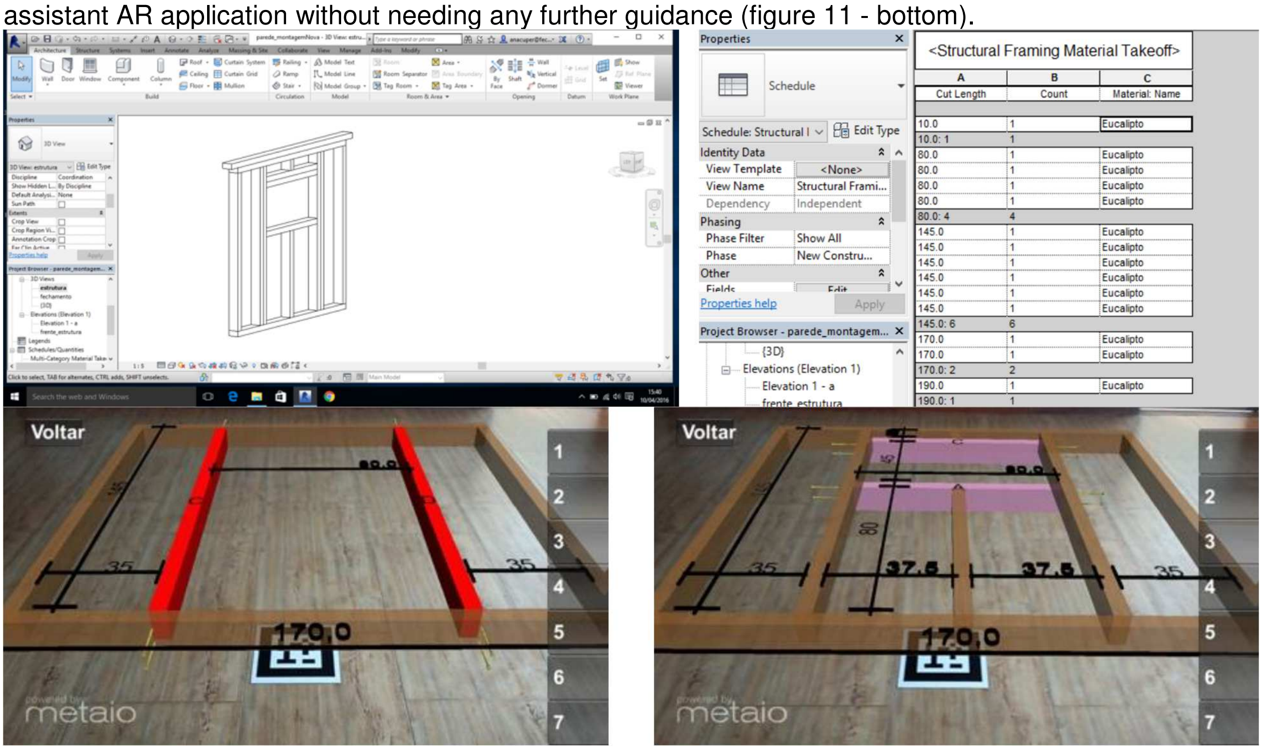


Figure 3: (top) Revit screenshots: wood-frame wall and the structural framing material takeoff; (bottom) the steps to assemble the wall through the AR application using AR mobile handheld and AR mobile smart glasses [119].

Another AR system created the above systems by continually scanning and checking the student assembly in real-time using the BIM model [120]. This provided the learner with direct feedback during the process that reduced the time required to complete the assembly. Moreover, it helped the students to understand the operation information better, compared to traditional workshops without the AR system. Pipe spool assembly is an activity that is suited to the system presented in this paper as 3D-scanning of small pieces is possible. However, it would not be possible to proceed with construction activities such as precast concrete wall installation or the assembly of longitudinal bars through a column.

4.1.2 Safety and Risks Prevention

An AR system has been developed to alert operators on worksites about dangerous events happening around them, such as vehicles circulating close by [4]. The system displays augmented information on operators' wearable glasses or notifies them on their smartphone about hazardous situations. The advantage of this system is that the safety management of an operator can also be checked by an expert in real-time from their office. However, this hazard avoidance system resulted in several issues. The system depends on multiple fixed cameras on site combined with the wearable glasses in order to compute distances between different elements on screen. The evaluation of safety level was not stable because tracking was often disrupted, full networking was required to run the system and the terrain elevation detection was not precise enough. In addition to the complexity of the setup of the system on the worksite (see figure 12), the proposed AR system was not ideal, even for student training.

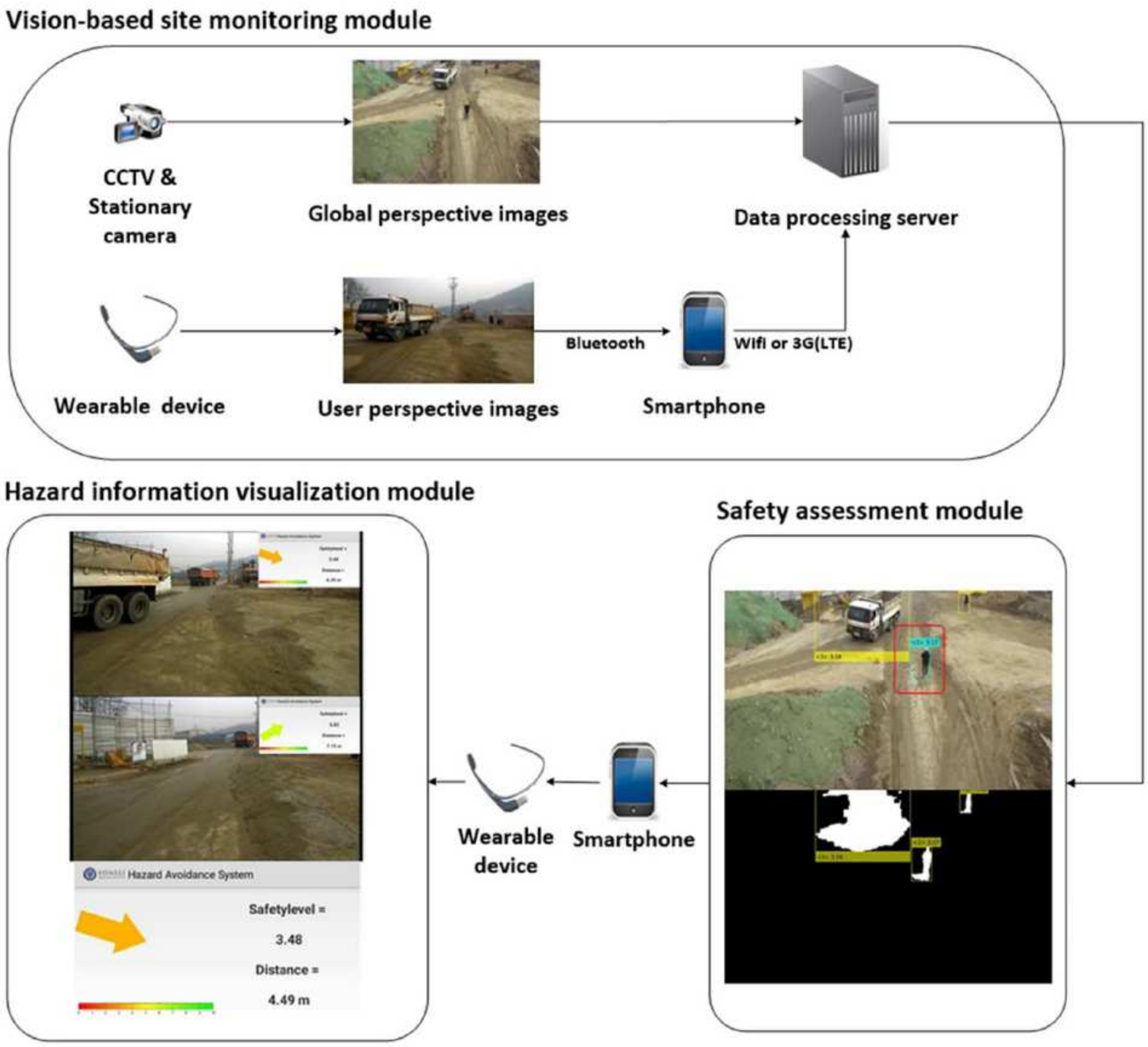


Figure 12: AR hazard avoidance system [4].

Two different frameworks for construction safety educational purposes were found in this SLR. VSES used different databases to generate VR safety scenarios that students could access on their smartphone by scanning a QR code [121] [122] [123]. VIFITS is an online system using 360-degree panoramas of worksites to illustrate scenarios [124]. Sessions are generated with different databases but can be customized using XML to set and integrate information together into web sessions. The advantage of virtual environments is that dangerous situations could be simulated to demonstrate safety rules and hazard avoidance without compromising the safety of the trainees as explained in section 3.2 of this paper. Additionally, by taking an active part on the VR training, learners pay better attention and are better able to absorb the concepts. Both studies used the national Occupational Safety and Health Agency (OSHA) safety rules, regulations, hazards and accident cases in their training material; however, their integration and matching with the virtual environment was not detailed enough to be reproduced. Another study also used the most frequently reported accident types as scenarios in their VR simulation [95]. The VR system was a simulation inside a simulated construction site displayed on a VR power-wall. The building used in the safety scenario used a BIM model designed in BIM software, however, BIM metadata were not utilized into the scenario.

Summary of findings

After comparing current research and use cases using AR and VR for the construction phase, the observable technology trends for VR activities and training lie predominantly in worksite operation and risk prevention or safety studies. AR is advantageous in the opportunity it provides to augment environments and objects with information and operation steps. However, some studies might not be adaptable to all worksite tasks such as the scan-vs-BIM method. There are many advantages in using VR for training, such as its immersive nature inside real-scale virtual worksite environments and the risk-free opportunities it can provide to operational staff and managers to experience and learn from dangerous situations to practice hazard avoidance and safety behaviors.

However, the scenarios proposed in these studies are too restrictive and hardcoded, limiting the number of scenarios and use cases available. The time required for modelling, animating, and developing might not be ideal for hundreds of worksite scenarios to be developed and this would require a different approach. For this reason, the next section of this review focuses on the architecture and data workflow that underpins communication between BIM and AR/VR, to facilitate authoring procedures and scenarios for AR/VR.

4.2 Data Workflow Between BIM and AR/VR Technology

The third research question addresses the main methodologies and frameworks applied to communication between BIM and AR or VR. Among 33 articles, 22 covered AR/VR integration and data workflow. In the literature, different workflows integrating BIM and AR/VR were proposed, developed or studied. Table 8 here below compares the different approaches in the publications and is followed by a discussion.

Research paper	***Technology and usage purpose***	***Type of process (auto – manual – custom development)***	***Number of steps from BIM to AR/VR***	***Software/Tools used***	***Use of a Cloud Server?***	***Is 3D optimization needed in the process?***	***Consultation of BIM metadata in AR/VR?***	***Formalized data architecture used?***
[126]	KMS viewer 4D	Auto	1	▪ Revit	no	no	no	no
[76] [78]	AR viewer 3D	Manual	3	▪ Archi-CAD ▪ ARToolKit	no	yes	no	no
[103]	KMS viewer 3D	Manual	2	▪ Revit ▪ VRApp	no	no	no	no
[127]	AR viewer 3D	Auto and manual	8	▪ ?	yes	no	no	no
[128]	AR viewer 3D	manual	?	▪ Unity ▪ Vuforia	no	no	no	no
[129]	AR viewer 3D	Custom development	?	▪ Ifcplusplus ▪ OpenSceneGraph	no	no	yes	IFC-SPF (STEP-File with .ifc extension)
[130]	VR viewer 3D multi-user	Manual	4	▪ Revit ▪ 3DsMax ▪ Unity ▪ PUN	no	yes	no	no
[131]	VR viewer 3D custom	Auto and custom development	4	▪ BIM software ▪ OpenBIMServer ▪ Unreal Engine	yes	no	no	IFC
[132]	KMS simulation	Manual	4	▪ Revit ▪ 3DsMax ▪ Unity	no	yes	no	no
[115] [133] [68]	AR viewer 3D	Manual and custom development	6	▪ Revit ▪ ACCEPT XML plugin ▪ 3DsMax ▪ Unity	no	yes	yes	IFC->XML
[65]	VR viewer 4D	Manual	4	▪ Revit ▪ 3DsMax ▪ Unity	no	yes	no	no

[134]	VR viewer 3D	Custom development	6	▪ Revit ▪ Revit plugin custom ▪ 3DsMax ▪ Unity ▪ 2 API	yes	yes	yes	no
[135]	AR/VR real-time navigation	Auto	?	▪ Unity ▪ Vuforia	no	?	no	no
[2]	VR viewer 3D multi-user	Auto	1	▪ Revit ▪ Fuzor	yes	no	yes	?
[136]	VR viewer 3D multi-user	Manual	1	▪ Revit ▪ IrisVR	no	no	yes	no
[137]	VR viewer 3D	Manual	4	▪ Revit ▪ 3DsMax ▪ Unity	no	yes	no	no
[138]	AR assistant tool	Manual and custom development	3	▪ Tekla ▪ IFC Parser ▪ MetroID BeamWeld software	no	no	no	no
[25]	AR viewer 3D	Manual and custom development	1	▪ Revit ▪ xBIM Toolkit	no	no	yes	IFC->XML

Table 8 - Comparative table of publications focused on BIM workflow for AR/VR integration

The research papers presented in table 8 show a selection of software used because each of them has a different purpose. The software offers 3D capabilities needed for complex modelling or meets construction-engineering requirements for construction.

When a specific AR/VR application is developed with the BIM model, this can be exported to a 3D engine where interaction features can be added and an application can be built. Often the BIM file format was not supported in the 3D engine, or the software could not support the large number of polygons generated by the BIM model when it was converted to a 3D model. The geometry from the BIM model, a volume model, can be exported to a 3D engine by transforming the file format into a surface model such as .fbx format and then optimized in 3D modelling software [139]. However, the BIM metadata may be lost during the process and may not remain available in the new application.

Thus 4 steps were required to move the data from the BIM software to the specific AR/VR application [130] [132] [65] [137] :

1) BIM geometry had to be exported from BIM software. BIM software such as Autodesk Revit are used to model 3D structures because building components contain a variety of available information, and professional drawings can be created automatically once the model is designed. However, only the geometry is exported as the 3D optimizer software in the following steps do not support the BIM file format.
2) Optimization with 3D modeling software.
3) A 3D game engine was required for its features and to build the application. Sometimes additional 3D content was added to the engine such as capacity to handle terrain and 3D point cloud data. Data from a database such as the safety rules could be added.
4) The AR/VR application needed to be executable with the converted BIM model.

The following figure 13 gathers BIM workflows available in the literature (part A in the figure) and the recent commercial solution workflows (part B in the figure) for data exchange from BIM to AR/VR. The 4 steps detailed below are numbered and represented in the workflow architecture (A, 1-2-3-4).

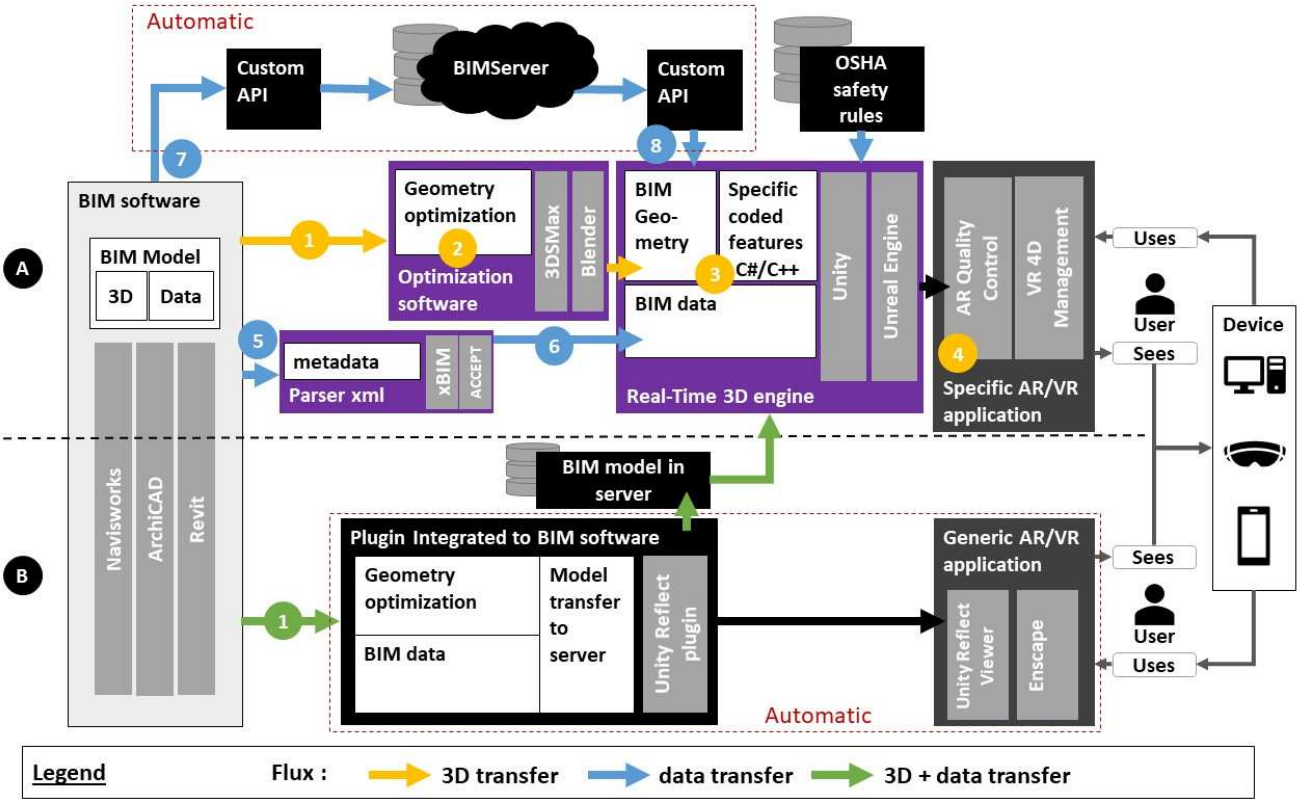


Figure 13: research and commercial solutions for BIM to AR/VR technology workflow architecture

To access the BIM metadata in addition to the BIM geometry, some efforts and custom developments were needed.

AR4C is an AR application [68] for which researchers developed a Revit plugin called ACCEPT XML plugin which imports the metadata of each BIM element in a .xml file associated with its “Element ID” (figure 13, A, 5). In the game engine, the building element (named by its “Element ID”) retrieved its metadata from the XML file (A, 6). This manual approach is limited as it takes time to make BIM data compatible with the 3D engine, and to convert the BIM model into 3D geometry. Each specific need must be developed by an IT team.

A similar framework was developed to use the “Element ID” of the building elements to retrieve the BIM metadata in the game engine [134]. However, due to a cloud server and custom developments, this method could update the BIM model and properties in the AR/VR application in real time directly from the BIM software. The authors noticed that “the entire process can be made reciprocal - when the user makes a change in the VR apps through the API plugins in VR apps, the change will be reflected in the Revit model via a reversed process.” This has however not been implemented. It is unclear whether it works in the other direction and therefore was not considered as a viable option. In figure 13, this automatic process is represented on the top of the figure (A, 7-8).

In [131], Authors studied the use of an OpenSource BIM server into which the BIM models would be imported and from which the BIM server would parse the geometry and import it with the BIM model data. After connecting the BIM server to the game engine using an API, the BIM project would be imported to the game engine editor and updated anytime a modification is made through the BIM server. The process of importing the model to the BIM server and then to the 3D engine was not covered in explicit details.

To access the BIM metadata in its AR environment, [129] proposed parsing the IFC file (which contains the BIM geometry and metadata) into a IFC-SPF (STEP-File with .ifc extension) using a C++ ifc library and to render the 3D model using the OpenSceneGraph library. The building element would appear in AR at its physical location using the visual pattern information integrated beforehand into the BIM metadata. This system required even more advanced IT skills for developing interaction features in the application.

A web-based solution has been developed using the xBIM libraries to read and add custom BIM properties to the IFC-based process model [25]. These libraries seem the most established and comprehensive for reading and writing BIM projects in an OpenBIM developed application. Web systems are also more comprehensible and flexible for customization but still require advanced IT skills. In the paper, there were no details regarding how the building element appears in VR from the WebGL interface where the BIM model is visualized in 3D with its metadata.

Recent commercial solutions have begun to proliferate, inspired by the above research papers. These include:

- The Unreal Engine which supports native .ifc files and provides an Autodesk Revit exporter for .rvt files to convert files into a format that Datasmith[2] can parse into the engine.
- A Revit plugin, called Enscape, which provides "a VR walkthrough of the fully rendered project – no uploading to the cloud or exporting to a separate program … any changes made in the CAD program are instantly visible in Enscape."
- Unity proposed a new plugin in 2020, called Reflect, which "brings multiple Revit models with all their BIM metadata to real-time 3D and maintain[s] a live link between them. It is also possible to create differentiated real-time BIM applications and customize the user experience by building on top of Unity Reflect with the Unity editor to build AR and VR experience."

For a non-specific application using AR/VR technology to visualize and consult the BIM model and data, the process is far simpler with only one step from the BIM software to access the BIM model in augmented or virtual reality (figure 13, part B). For example, a solution that automatically imports the BIM model to the VR environment can be used [2] or the BIM model can be imported manually into the VR application [136]. Both solutions facilitate BIM data consultation. However, neither option allows the user to modify the original BIM file within VR.

Summary of findings

This section addressed the third aim of the SLR that was to study the different workflows integrating BIM and AR/VR. Notable progress has been made in research on the integration of BIM geometry and metadata into augmented or virtual reality over the last decade. A commercial solution provided a generic application with restricted features. A potential manual workflow included 4 steps from the BIM software to a specific AR/VR application; however, this solution did not allow access of the BIM metadata. Another solution integrates custom frameworks developed to access the BIM metadata with features added to a 3D game engine in order to build an AR/VR application. However, once the BIM model was imported, there was no possibility to modify the original BIM file in the augmented or virtual reality environment. None of these workflows led to a back loop where each update in AR/VR was reported to the original BIM file. This is notable because object hierarchies and 3D coordinates in BIM models (in the .ifc format) are completely different once transformed to be integrated to a 3D engine. Much work is needed to remap the information back into the BIM format.

4.3 Challenges related to AR/VR scenarios using BIM 3D and metadata

[2] Datasmith available at https://www.unrealengine.com/en-US/datasmith

A significant challenge to integrating BIM and AR/VR is that it is difficult to find a workflow that enables the modification of the original BIM project once it is imported into the augmented or virtual environment. For example, a feature that would allow an expert in safety training and risks prevention to create a VR/AR course and save the information into the BIM model is not possible at present. Moreover, this feature would need to store training data in another format such as a CSV or XML file. Another challenge for the integration of these systems is that they require tedious work from an AEC professional, who has the jobsite knowledge for on-site operations assistance or training but is not an IT developer. An AEC professional could use commercial solution options that are limited by generic features. These solutions were not developed for the creation of scenarios but rather for precise applications like reviewing a model or on-site quality control. Currently, applications center on the consultation of metadata and object manipulation and no complex interactions are possible.

In this SLR, the publication that comes closest to a scenario where the professional was able to author a VR/AR training from the BIM model was [119]. The different phases of construction of the wooden frame were numbered and stored in the BIM model via the BIM software and then reused to script a training developed in AR. However, no details were provided on the formalization of the data or the use of a specific architecture. Further research would therefore study existing data architectures that would allow the creation of AR/RV scenarios from BIM models and the knowledge stored in them. An additional challenge is the relationship of the virtual element (to be operated) to the scripting of the different steps, for example while developing a scripted training for work on-site. Detailed operational knowledge (such as how to assemble two parts of the wooden frame) must be stored in the BIM element to be reused in the 3D engine in a way intelligible in the scenario that would justify the step. To do so, a formalism between the BIM element, the task and its AR/VR scenario should be developed. None of the publications in this SLR proposed such a formalism.

To overcome these limitations, semantic modelling and VR/AR training scenarios are studied. These works predominantly used modeling approaches based on the Unified Modeling Language (UML) formalism [140][141] or on ontologies [142][143] to represent procedural scenarios and knowledge needed for AR/VR training. The emergence of semantic web technologies and the concept of a semantic construction digital twin are promising trends in tackling interoperability issues between various data and structures in the AEC/FM industry [144]. In order to apply ontologies in construction, BIM files in IFC format could be converted to RDF/XML format [145] or to OWL/XML format (called ifcOWL) [146] however interoperability between BIM and AR/VR is still challenging.

Future works could focus on ontologies and UMLs in relation to parametric data and BIM modeling. Moreover, more research must be conducted to define interactions in virtual environments associated with procedures and scenarios. Some promising paths for research include using web based semantic ontology, [147] combining BIM 4D and job hazard analysis for preventative on-site safety or studying existing industry research such as [148] which is an industrial ontology for operation in virtual and augmented scenes.

5 CONCLUSION

Virtual and augmented reality are tools that have real impacts in AEC projects and their different phases. This study shows that technologies are used differently in different phases: VR for the design phase of the project, AR and VR for the construction phase and AR for the FM phase. This study shows that research trends over the last ten years have been driven by the release of increasingly sophisticated AR/VR devices and frameworks. VR is used preferentially when the device is a headset connected to a PC, for design reviews and simulation activities. AR is more often used with tablet and mobile devices for maintenance, quality control and construction management activities.

The least frequently identified activities and trainings in the literature were site operations and prevention and safety. This is confirmed by the lack of publications on 8D BIM "safety by design." The activities and learning of jobsite operations were preferentially studied using AR that is promising in its ability to phase work elements in the construction design software. Learning, preventive and safety activities in VR have received a fair amount of academic attention. This has resulted beneficially in the integration of national safety rules, although scenarios remain scarce and rigid.

With difficulty, BIM can be integrated with VR tools to collaborate on 3D and 4D BIM data and with AR tools to visualize 3D models and their metadata for 3D, 4D or 7D BIM uses. Higher more complex BIM dimensions were less represented in the SLR. Once parametric data was included in a virtual environment or augmented via its digital model it could not be modified because the file format had been transformed. Commercial solutions have provided simplified workflows but remain generic 3D applications that cannot be adapted for scripting or training in virtual and augmented environments.

4 steps were required to bring the BIM model from the BIM software into a newly developed software application. Firstly the geometry had to be optimized, then it had to be parsed into a game engine, features had to be added to the engine and lastly an executable application had to be built for a worksite training application in AR or VR. However, all the knowledge stored in the BIM project could not be utilized which limited the number of scenarios developed. This workflow does not allow the user to access to BIM metadata and requires the developer to program a framework to customize the workflow, for example, by retrieving the BIM metadata from the BIM software, importing it and matching it to a 3D model in a game engine.

One source of complexity in developing learning activities for worksite operations in AR or VR is the relationship of the virtual element (to be operated) to the scripting of the different steps. The publications presented in the study do not present any data or knowledge models. Given these and the summary of achievements and challenges in table 9, further research could focus on ontologies and UMLs in relation to parametric data, BIM modeling and scripting in augmented or virtual environments.

AR/VR	Achievements	Challenges
Technology	- VR tethered devices are powerful enough for displaying large BIM model. - VR headset and AR framework have facilitated the adoption of AR/VR technologies.	- Lack of accurate tracking technology for matching BIM models and data with the physical twin during the construction phase. - Needs of automatic BIM model simplification for VR/AR mobile device with less computing power. - Integration of 5G and cloud computing AR/VR rendering to make technologies accessible from everywhere with any device.
Activities	- Numerous proofs of concept concerning activities with 3D model visualization and simple interactions (mainly in Design review and Construction management activities)	- Needs of AR/VR scenarios authoring tools with complex and job-specific interactions, in activities such as On-site operation or Safety and risk prevention.
Worksite operations and risk prevention or safety studies	- Existing use case shows the effectiveness of VR for workers risk and safety trainings. - AR provides step-by-step procedure for assisting operator on worksite during the construction phase	- Lack of standards and/or framework to author step-by-step procedure or training scenario in AR/VR applications from BIM data. - Needs of contextualized training based on the BIM current state during construction phase.
BIM and data flow architecture	- 3D BIM used in AR/VR applications for visualization of 3D model and collaboration on BIM project is in constant upward trend.	- Lack of knowledge management IT architecture and process to share job expertise (e.g. QHSE) in AR/VR training applications. - Needs of architecture allowing updating BIM data from AR/VR applications and a closer integration between the digital twin and AR/VR human machine interfaces.

Table 9 - Summary of achievements and challenges in AR/VR-BIM data flow

References

[1] K. Beddiar, C. Grellier, E. Woods, Construction 4.0 - Réinventer le bâtiment grâce au numérique : BIM, DfMA, Lean Management, DUNOD, 2019 (ISBN 978-2-10-079050-0).

[2] R. Zaker, E. Coloma, Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study, Visualization in Engineering. 6 (2018) 4. https://doi.org/10.1186/s40327-018-0065-6.

[3] J. Imaizumi, Assessment of the Process for Designing an Apartment Building through IM & VR, International Review for Spatial Planning and Sustainable Development. 5 (2017) pp. 45–54. https://doi.org/10.14246/irspsd.5.1_45.

[4] K. Kim, H. Kim, H. Kim, Image-based construction hazard avoidance system using augmented reality in wearable device, Automation in Construction. 83 (2017) pp. 390–403. https://doi.org/10.1016/j.autcon.2017.06.014.

[5] C. Koch, M. Neges, M. König, M. Abramovici, BIM-based Augmented Reality for Facility Maintenance using Natural Markers, European Group for Intelligent Computing in Engineering, EG-ICE 2012 - International

Workshop: Intelligent Computing in Engineering. (2012) pp. 94–96. http://www.proceedings.com/24294.html (accessed October 19, 2021).

[6] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Automation in Construction. 19 (2010) pp. 988–999. https://doi.org/10.1016/j.autcon.2010.09.002.

[7] S. Meža, Ž. Turk, M. Dolenc, Component based engineering of a mobile BIM-based augmented reality system, Automation in Construction. 42 (2014) pp. 1–12. https://doi.org/10.1016/j.autcon.2014.02.011.

[8] M. Johansson, M. Roupé, M. Viklund Tallgren, From BIM to VR - Integrating immersive visualizations in the current design process, Fusion-Proceedings of the 32nd ECAADe Conference-Volume 2 (ECAADe 2014). 195 (2014) pp. 261–269. http://ecaade.org/downloads/eCAADe2014_volume2.pdf (accessed October 19, 2021).

[9] L. Barazzetti, F. Banfi, Historic BIM for Mobile VR/AR Applications, Mixed Reality and Gamification for Cultural Heritage, Springer International Publishing, Cham, 2017: pp. 271–290. https://doi.org/10.1007/978-3-319-49607-8_10.

[10] J. MacDonald, Systematic Approaches to a Successful Literature Review, Journal of the Canadian Health Libraries Association / Journal de l'Association Des Bibliothèques de La Santé Du Canada. 34 (2014) 46. https://doi.org/10.5596/c13-009.

[11] S. Rankohi, L. Waugh, Review and analysis of augmented reality literature for construction industry, Visualization in Engineering. 1 (2013) 9. https://doi.org/10.1186/2213-7459-1-9.

[12] S. Ahmed, A Review on Using Opportunities of Augmented Reality and Virtual Reality in Construction Project Management, Organization, Technology and Management in Construction: An International Journal. 11 (2019) pp. 1839–1852. https://doi.org/10.2478/otmcj-2018-0012.

[13] S. Bhoir, B. Esmaeili, State-of-the-Art Review of Virtual Reality Environment Applications in Construction Safety, American Society of Civil Engineers, Reston, VA, 2015: pp. 457–468. https://doi.org/10.1061/9780784479070.040.

[14] X. Li, W. Yi, H.-L. Chi, X. Wang, A.P.C. Chan, A critical review of virtual and augmented reality (VR/AR) applications in construction safety, Automation in Construction. 86 (2018) pp. 150–162. https://doi.org/10.1016/j.autcon.2017.11.003.

[15] N. Azimi, B. Fakhim, BIM + AR/VR: A review on BIM's New Technologies and its Effect in Hospital construction projects, 5th Congress for Hospital Build and Facility Management. (2018). https://en.civilica.com/doc/828057/ (accessed October 19, 2021).

[16] C. Calderon-Hernandez, Lean, BIM and Augmented Reality Applied in the Design and Construction Phase: A Literature Review, International Journal of Innovation, Management and Technology. (2018) pp. 60–63. https://doi.org/10.18178/ijimt.2018.9.1.788.

[17] N.M. Shamsudin, N.H.Ni. Mahmood, A.R.A. Rahim, S.F. Mohamad, M. Masrom, Virtual Reality for Construction Occupational Safety and Health Training: A Review, Advanced Science Letters. 24 (2018) pp. 2444–2446. https://doi.org/10.1166/asl.2018.10976.

[18] P. Wang, P. Wu, J. Wang, H.-L. Chi, X. Wang, A Critical Review of the Use of Virtual Reality in Construction Engineering Education and Training, International Journal of Environmental Research and Public Health. 15 (2018) 1204. https://doi.org/10.3390/ijerph15061204.

[19] A. Tabrizi, P. Sanguinetti, Literature Review of Augmented Reality Application in the Architecture, Engineering, and Construction Industry with Relation to Building Information, Advanced Methodologies and Technologies in Engineering and Environmental Science, 2019 pp. 61–73. https://doi.org/10.4018/978-1-5225-7359-3.ch005.

[20] A. Sidani, F.M. Dinis, L. Sanhudo, J. Duarte, J. Santos Baptista, J. Poças Martins, A. Soeiro, Recent Tools and Techniques of BIM-Based Virtual Reality: A Systematic Review, Archives of Computational Methods in Engineering. 28 (2021) pp. 449–462. https://doi.org/10.1007/s11831-019-09386-0.

[21] A.C. Correa dos Santos, M.E. Delamaro, F.L.S. Nunes, The Relationship between Requirements Engineering and Virtual Reality Systems: A Systematic Literature Review, XV Symposium on Virtual and Augmented Reality, IEEE, 2013 pp. 53–62. https://doi.org/10.1109/SVR.2013.52.

[22] R. Palmarini, J.A. Erkoyuncu, R. Roy, H. Torabmostaedi, A systematic review of augmented reality applications in maintenance, Robotics and Computer-Integrated Manufacturing. 49 (2018) pp. 215–228. https://doi.org/10.1016/j.rcim.2017.06.002.

[23] D. Zhao, J. Lucas, Virtual reality simulation for construction safety promotion, International Journal of Injury Control and Safety Promotion. 22 (2015) pp. 57–67. https://doi.org/10.1080/17457300.2013.861853.

[24] R. Sacks, U. Gurevich, B. Belaciano, Hybrid Discrete Event Simulation and Virtual Reality Experimental Setup for Construction Management Research, Journal of Computing in Civil Engineering. 29 (2015) 04014029. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000366.

[25] M. Mirshokraei, C.I. de Gaetani, F. Migliaccio, A Web-Based BIM–AR Quality Management System for Structural Elements, Applied Sciences. 9 (2019) 3984. https://doi.org/10.3390/app9193984.

[26] Z. Asgari, F.P. Rahimian, Advanced Virtual Reality Applications and Intelligent Agents for Construction Process Optimisation and Defect Prevention, Procedia Engineering. 196 (2017) pp. 1130–1137. https://doi.org/10.1016/j.proeng.2017.08.070.

[27] Y.-T. Kim, J.-Y. Lee, S.-H. Lee, J.-S. Choi, Construction and inspection management system using mobile augmented reality, 19th Korea-Japan Joint Workshop on Frontiers of Computer Vision, IEEE, 2013 pp. 93–96. https://doi.org/10.1109/FCV.2013.6485467.

[28] Y. Zhou, H. Luo, Y. Yang, Implementation of augmented reality for segment displacement inspection during tunneling construction, Automation in Construction. 82 (2017) pp. 112–121. https://doi.org/10.1016/j.autcon.2017.02.007.

[29] W. Feng, W. Wei, L. Xiuluo, Implementation of the Building Decoration Design Demonstration System Based on Virtual Reality, Advances in Intelligent and Soft Computing, Springer, 2012 pp. 891–898. https://doi.org/10.1007/978-3-642-27334-6_106.

[30] T. Ai, H. Kang, Y.O. Ren, Realizes 3D Simulation of Campus Construction Based on Virtual Reality, Applied Mechanics and Materials. 738–739 (2015) pp. 1349–1352. https://doi.org/10.4028/www.scientific.net/AMM.738-739.1349.

[31] L.R. Suzuki, K. Brown, S. Pipes, J. Ibbotson, Smart building management through augmented reality, IEEE International Conference on Pervasive Computing and Communication Workshops (PERCOM WORKSHOPS), IEEE, 2014 pp. 105–110. https://doi.org/10.1109/PerComW.2014.6815174.

[32] Alcínia Zita Sampaio, Miguel M. Ferreira, Daniel P. Rosário, Virtual Reality Used in the Lighting System Management of a Building, Journal of Civil Engineering and Architecture. 6 (2012). https://doi.org/10.17265/1934-7359/2012.06.005.

[33] Alcínia Zita Sampaio, Building Maintenance Supported on Virtual Reality Environments: Roofs and Walls, Journal of Civil Engineering and Architecture. 10 (2016). https://doi.org/10.17265/1934-7359/2016.01.001.

[34] N. Gu, V. Singh, X. Wang, Applying augmented reality for data interaction and collaboration in BIM, New Frontiers - Proceedings of the 15th International Conference on Computer-Aided Architectural Design in Asia, CAADRIA 2010 pp. 511–520.

https://nova.newcastle.edu.au/vital/access/services/Download/uon:10095/ATTACHMENT01 (accessed October 19, 2021).

[35] P. Orihuela, M. Noel, S. Pacheco, J. Orihuela, C. Yaya, R. Aguilar, 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 2019, pp. 1105–1116. https://doi.org/10.24928/2019/0220.

[36] C. Calderon-Hernandez, D. Paes, J. Irizarry, X. Brioso, Comparing Virtual Reality and 2-Dimensional Drawings for the Visualization of a Construction Project, Computing in Civil Engineering 2019, American Society of Civil Engineers, Reston, VA, 2019 pp. 17–24. https://doi.org/10.1061/9780784482421.003.

[37] H.-L. Chi, S.-C. Kang, X. Wang, Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, Automation in Construction. 33 (2013) pp. 116–122. https://doi.org/10.1016/j.autcon.2012.12.017.

[38] A.R.M. Cuperschmid, R.C. Ruschel, M.R. de Freitas, Technologies that support Augmented Reality Applied to Architecture and Construction, Universidade Federal Do Rio de Janeiro, 2012. https://www.academia.edu/download/32990894/Proarq19_TechnologiesReality_CuperschmidRuschelFreitas.pdf (accessed October 19, 2021).

[39] S. Wang, Integrated Digital Building Delivery System Based on BIM and VR Technology, Applied Mechanics and Materials. 380–384 (2013) pp. 3193–3197. https://doi.org/10.4028/www.scientific.net/AMM.380-384.3193.

[40] A.Z. Sampaio, Education in engineering: BIM and VR technologies improving collaborative projects, 4th International Conference on Civil Engineering Education: Challenges for the Third Millennium. (2018) pp. 48–57. http://congress.cimne.com/euceet2018/admin/files/filepaper/p2.pdf (accessed October 19, 2021).

[41] A. Sampaio, A. Gomes, D. Rosário, Collaborative maintenance and construction of buildings supported on Virtual Reality technology, Conference Information Systems and Technologies (CISTI). (2011) pp. 47–63. https://ieeexplore.ieee.org/document/5974196 (accessed October 19, 2021).

[42] Z. Yang, K. Kensek, Building Information Modeling and Virtual Reality: Workflows for Design and Facility Management, ARCC Conference Repository. (2018) 266–273. https://www.arcc-journal.org/index.php/repository/article/download/546/435 (accessed October 19, 2021).

[43] H. Yilei, S. Samjhana, O. Temitope, Comparing the Functionality between Virtual Reality and Mixed Reality for Architecture and Construction Uses, Journal of Civil Engineering and Architecture. 13 (2019). https://doi.org/10.17265/1934-7359/2019.07.001.

[44] J.S. Kim, T. Leathem, J. Liu, Comparing Virtual Reality Modalities and 360 Photography in a Construction Management Classroom, 55th ASC Annual International Conference Proceedings. (2019) 221–228. https://www.semanticscholar.org/paper/Comparing-Virtual-Reality-Modalities-and-360%C2%B0-in-a-Kim-Leathem/d4a00152c80e906ce23c64b6642d40d45660250d (accessed October 19, 2021).

[45] Y. Gao, V.A. Gonzalez, T.W. Yiu, The effectiveness of traditional tools and computer-aided technologies for health and safety training in the construction sector: A systematic review, Computers and Education. 138 (2019) pp. 101–115. https://doi.org/10.1016/j.compedu.2019.05.003.

[46] J. Goulding, W. Nadim, P. Petridis, M. Alshawi, Construction industry offsite production: A virtual reality interactive training environment prototype, Advanced Engineering Informatics. 26 (2012) pp. 103–116. https://doi.org/10.1016/j.aei.2011.09.004.

[47] J. Kang, K. Kuncham, BIM CAVE for 4D immersive virtual reality, Creative Construction Conference 2014. (2014) pp. 568–574. http://2015.creative-construction-conference.com/wp-content/uploads/2015/01/CCC2014_J_Kang.pdf (accessed October 19, 2021).

[48] M. Wolf, J. Teizer, J.H. Ruse, Case Study on Mobile Virtual Reality Construction Training, Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC, 2019: pp. 1231–1237. https://doi.org/10.22260/ISARC2019/0165.

[48] C. Wang, H. Li, S.Y. Kho, VR-embedded BIM immersive system for QS engineering education, Computer Applications in Engineering Education. 26 (2018) pp. 626–641. https://doi.org/10.1002/cae.21915.

[50] Y.C. Lin, Y.P. Chen, H.W. Yien, C.Y. Huang, Y.C. Su, Integrated BIM, game engine and VR technologies for healthcare design: A case study in cancer hospital, Advanced Engineering Informatics. 36 (2018) pp. 130–145. https://doi.org/10.1016/j.aei.2018.03.005.

[51] V. Kasireddy, Z. Zou, B. Akinci, J. Rosenberry, Evaluation and Comparison of Different Virtual Reality Environments towards Supporting Tasks Done on a Virtual Construction Site, Construction Research Congress 2016: Old and New Construction Technologies Converge in Historic San Juan - Proceedings of the 2016 Construction Research Congress, CRC 2016, American Society of Civil Engineers, Reston, VA, 2016 pp. 2371–2381. https://doi.org/10.1061/9780784479827.236.

[52] S. Krakhofer, M. Kaftan, Augmented reality design decision support engine for the early building design stage, 20th International Conference on Computer-Aided Architectural Design Research in Asia: Emerging Experiences in the Past, Present and Future of Digital Architecture, CAADRIA 2015 pp. 231–240. http://papers.cumincad.org/cgi-bin/works/Show?caadria2015_188 (accessed October 19, 2021).

[53] S. Kivrak, G. Arslan, Using Augmented Reality to Facilitate Construction Site Activities, Advances in Informatics and Computing in Civil and Construction Engineering, Springer International Publishing, Cham, 2019 pp. 215–221. https://doi.org/10.1007/978-3-030-00220-6_26.

[54] L. Jinyu, Y. Bangbang, C. Danpeng, W. Nan, Z. Guofeng, B. Hujun, Survey and evaluation of monocular visual-inertial SLAM algorithms for augmented reality, Virtual Reality & Intelligent Hardware. 1 (2019) pp. 386–410. https://doi.org/10.1016/j.vrih.2019.07.002.

[55] P.H. Diao, N.J. Shih, BIM-based AR maintenance system (BARMS) as an intelligent instruction platform for complex plumbing facilities, Applied Sciences (Switzerland). 9 (2019) 1592. https://doi.org/10.3390/app9081592.

[56] X.S. Lee, M.F. Khamidi, Z.S. See, T.J. Lees, C. Chai, Augmented reality for n dimensional building information modelling: Contextualization, Customization and Curation, Proceedings of the 2016 International Conference on Virtual Systems and Multimedia, VSMM 2016, IEEE, 2016 pp. 1–5. https://doi.org/10.1109/VSMM.2016.7863152.

[57] M. Olbrich, H. Graf, S. Kahn, T. Engelke, J. Keil, P. Riess, S. Webel, U. Bockholt, G. Picinbono, Augmented reality supporting user-centric building information management, Visual Computer. 29 (2013) pp. 1093–1105. https://doi.org/10.1007/s00371-013-0840-2.

[58] S. Xiang, R. Wang, C. Feng, Towards mobile projective AR for construction co-robots, Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, pp. 1106–1113. https://doi.org/10.22260/isarc2019/0147.

[59] J. Kieferle, U. Woessner, BIM Interactive - About Combining BIM and Virtual Reality, 33rd Education and Research in Computer Aided Architectural Design in Europe Conference, Vienna, Austria, pp. 69–75. http://papers.cumincad.org/data/works/att/ecaade2015_329.content.pdf (accessed October 19, 2021).

[60] P. Herbers, M. König, Indoor localization for augmented reality devices using BIM, point clouds, and template matching, Applied Sciences (Switzerland). 9 (2019) 4260. https://doi.org/10.3390/app9204260.

[61] X. Luo, C.-K. Wong, J. Chen, A Multi-player Virtual Reality-based Education Platform for Construction Safety, 16th International Conference on Computing in Civil and Building Engineering. (2016).

https://pdfs.semanticscholar.org/5871/24fa433a771886535b4290e6c538a6802557.pdf (accessed October 19, 2021).

[62] A. Abbas, M. Choi, J.O. Seo, S.H. Cha, H. Li, Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects, KSCE Journal of Civil Engineering. 23 (2019) pp. 4972–4983. https://doi.org/10.1007/s12205-019-0898-0.

[63] A. Shirazi, A.H. Behzadan, Assessing the Pedagogical Value of Augmented Reality-Based Learning in Construction Engineering, Proceedings of the 13th International Conference on Construction Applications of Virtual Reality (CONVR), London, UK. (2013) pp. 416–426. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.722.7973&rep=rep1&type=pdf (accessed October 19, 2021).

[64] M. Froehlich, S. Azhar, Investigating virtual reality headset applications in construction, 52nd ASC Annual International Conference Proceedings, 2016. http://ascpro0.ascweb.org/archives/cd/2016/paper/CPRT195002016.pdf (accessed October 19, 2021).

[65] C. Boton, Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation, Automation in Construction. 96 (2018) pp. 1–15. https://doi.org/10.1016/j.autcon.2018.08.020.

[66] M. Uimonen, M. Hakkarainen, Accessing BIM-Related Information through AR, Adjunct Proceedings - IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018. (2018) pp. 399–400. https://doi.org/10.1109/ISMAR-Adjunct.2018.00115.

[67] M. Lin, Augmented Reality Solution for Facility Maintenance with BIM, Master’s Thesis dissertation, 2019. https://aaltodoc.aalto.fi/handle/123456789/40873 (accessed October 19, 2021).

[68] J. Ratajczak, M. Riedl, D. Matt, BIM-based and AR Application Combined with Location-Based Management System for the Improvement of the Construction Performance, Buildings. 9 (2019) 118. https://doi.org/10.3390/buildings9050118.

[69] T. Sulbaran, L. Frederick, J. Iii, Utilizing a Collaborative Virtual Reality Environment as a Training Tool for Construction Students, ASEE Annual Conference & Exposition. (2012). https://peer.asee.org/utilizing-a-collaborative-virtual-reality-environment-as-a-training-tool-for-construction-students (accessed October 19, 2021).

[70] D. Paes, J. Irizarry, A Usability Study of an Immersive Virtual Reality Platform for Building Design Review: Considerations on Human Factors and User Interface, Construction Research Congress 2018, American Society of Civil Engineers, Reston, VA, 2018 pp. 419–428. https://doi.org/10.1061/9780784481264.041.

[71] T.M. Zaki, C.A. Khalil, Qr-Coded Clash-Free Drawings: an Integrated System of BIM and Augmented Reality To Improve Construction Project Visualization, 5th International Construction Specialty Conference of the Canadian Society for Civil Engineering (ICSC), 2015 pp. 1–10. https://doi.org/10.13140/RG.2.1.1889.8085.

[72] S. Kivrak, G. Arslan, M. Tuncan, Implementing Augmented Reality in Construction Projects, Applied Mechanics and Materials. 719–720 (2015) pp. 197–201. https://doi.org/10.4028/www.scientific.net/amm.719-720.197.

[73] J.C.P. Cheng, K. Chen, W. Chen, C.T. Li, A BIM-Based Location Aware AR Collaborative Framework for Facility Maintenance Management, Journal of Information Technology in Construction. 24 (2016) pp. 30–39. https://www.itcon.org/papers/2019_19-ITcon-Chen.pdf (accessed October 19, 2021).

[74] W. Natephra, A. Motamedi, T. Fukuda, N. Yabuki, Integrating building information modeling and virtual reality development engines for building indoor lighting design, Visualization in Engineering. 5 (2017) 19. https://doi.org/10.1186/s40327-017-0058-x.

[75] L. Filipe, D. Viana, Simulation of a bridge deck construction using precast beams supported in Virtual Reality technology, 2012 pp. 1–10. https://pdfs.semanticscholar.org/7490/e266b53f13f26ba07dac39453aa63ef487eb.pdf (accessed October 19, 2021).

[76] J.Y. Lee, O.S. Kwon, J.S. Choi, C.S. Park, A study on construction defect management using augmented reality technology, International Conference on Information Science and Applications, ICISA 2012, IEEE, 2012 pp. 1–6. https://doi.org/10.1109/ICISA.2012.6220933.

[77] C.S. Park, D.Y. Lee, O.S. Kwon, X. Wang, A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template, Automation in Construction. 33 (2013) pp. 61–71. https://doi.org/10.1016/j.autcon.2012.09.010.

[78] O.S. Kwon, C.S. Park, C.R. Lim, A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality, Automation in Construction. 46 (2014) pp. 74–81. https://doi.org/10.1016/j.autcon.2014.05.005.

[79] A. Heinzel, S. Azhar, A. Nadeem, Uses of Augmented Reality Technology during Construction Phase, 9th International Conference of Construction in the Twenty-First Century (CITC9), 2017. https://www.citcglobal.com/citc-9-papers (accessed October 19, 2021).

[80] A. Ebner, F. Kammergruber, T. Horenburg, W.A. Günthner, Logistics and Layout Planning of Construction Equipment on a VR-Multi-Touch-Table, Proceedings of 12th International Conference on Construction Applications of Virtual Reality, 2012: pp. 552–560. https://www.worldcat.org/title/convr-2012-proceedings-of-the-12th-international-conference-on-construction-applications-of-virtual-reality-november-1-2-2012-taipei-taiwan/oclc/930948300 (accessed October 19, 2021).

[81] E. Ginters, A. Cirulis, G. Blums, Markerless Outdoor AR-RFID Solution for Logistics, Procedia Computer Science. 25 (2013) pp. 80–89. https://doi.org/10.1016/j.procs.2013.11.010.

[82] E.H.L. Cheung, S.T. Ng, Applying Virtual Reality to Improve the Construction Logistics of High-rise Modular Integrated Construction, Modular and Offsite Construction (MOC) Summit Proceedings. (2019) pp. 76–83. https://doi.org/10.29173/mocs79.

[83] R. Liu, F. Zhang, F. Liu, G. Wang, Case Study of BIM+ AR Technology in China Power Engineering Construction Materials Management, 2019. https://wwww.easychair.org/publications/preprint_download/GpHV (accessed October 19, 2021).

[84] B. Kim, C. Kim, H. Kim, Interactive Modeler for Construction Equipment Operation Using Augmented Reality, Journal of Computing in Civil Engineering. 26 (2012) pp. 331–341. https://doi.org/10.1061/(asce)cp.1943-5487.0000137.

[85] A. Fenais, N. Smilovsky, S.T. Ariaratnam, S.K. Ayer, A Meta-Analysis of Augmented Reality Challenges in the Underground Utility Construction Industry, Construction Research Congress 2018, American Society of Civil Engineers, Reston, VA, 2018 pp. 80–89. https://doi.org/10.1061/9780784481295.009.

[86] S. Kıvrak, G. Arslan, Using Augmented Reality in Construction Project Activities, Tamap Journal of Engineering. (2019). https://doi.org/10.29371/2018.3.64.

[87] M. Habibnezhad, J. Puckett, M.S. Fardhosseini, L.A. Pratama, A Mixed VR and Physical Framework to Evaluate Impacts of Virtual Legs and Elevated Narrow Working Space on Construction Workers' Gait Pattern, Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, pp. 1057–1064. https://doi.org/10.22260/ISARC2019/0141.

[88] K. Patil, S. Bhandari, S. Ayer, Matthew. Hallowell, Potential for Virtual Reality and Haptic Feedback to Enhance Learning Outcomes Among Construction Workers, Proceedings of the 18th International Conference on Construction Applications of Virtual Reality, 2018 pp. 246–255.

https://www.worldcat.org/title/proceedings-of-the-18th-international-conference-on-construction-applications-of-virtual-reality/oclc/1082456397 (accessed October 19, 2021).

[89] P. Limsupreeyarat, N. Yabuki, T. Tongthong, Toward the improvement of safety planning for construction activities performed at high elevation by using augmented reality, 17th International Workshop on Intelligent Computing in Engineering. (2019). https://www.semanticscholar.org/paper/Toward-the-improvement-of-safety-planning-for-at-by-Limsupreeyarat-Yabuki/ac81e709848fa6e44f4bc2b3b3fbc4db3c34d41a (accessed October 19, 2021).

[90] K.L. Mugumya, J.Y. Wong, A. Chan, C.C. Yip, The role of linked building data (LBD) in aligning augmented reality (AR) with sustainable construction, International Journal of Innovative Technology and Exploring Engineering. 8 (2019) pp. 366–372. https://doi.org/10.35940/ijitee.F1074.0486S419.

[91] H. Si, Z. Yang, Research of the application of virtual reality in green construction, Advanced Materials Research. 462 (2012) pp. 592–597. https://doi.org/10.4028/www.scientific.net/AMR.462.592.

[92] D.A.S. Samarasinghe, S.A. Latif, N. Baghaei, Virtual reality models for promoting learners engagement in construction studies, IEEE Global Engineering Education Conference, EDUCON, IEEE, 2019 pp. 1331–1335. https://doi.org/10.1109/EDUCON.2019.8725120.

[93] J. Grazina, N. Cachadinha, Towards a Systematic Production Progress Assessment Based on AR on BIM – Prerequisites and Functional Requirements, Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, London, UK. (2013) pp. 30–31. https://itc.scix.net/pdfs/convr-2013-31.pdf (accessed October 19, 2021).

[94] J. Davidson, J. Fowler, C. Pantazis, M. Sannino, J. Walker, M. Sheikhkhoshkar, F.P. Rahimian, Integration of VR with BIM to facilitate real-time creation of bill of quantities during the design phase: a proof of concept study, Frontiers of Engineering Management. 7 (2020) pp. 396–403. https://doi.org/10.1007/s42524-019-0039-y.

[95] R. Sacks, A. Perlman, R. Barak, Construction safety training using immersive virtual reality, Construction Management and Economics. 31 (2013) pp. 1005–1017. https://doi.org/10.1080/01446193.2013.828844.

[96] N. Blinn, M. Robey, H. Shanbari, R.R.A. Issa, Using Augmented Reality to Enhance Management Educational Experiences Construction, 32nd CIB W78 Conference, Eindhoven, The Netherlands, pdfs.semanticscholar.org, 2015 pp. 69–78. https://itc.scix.net/pdfs/w78-2015-paper-007.pdf (accessed October 19, 2021).

[97] A.Z. Sampaio, M.M. Ferreira, D.P. Rosário, O.P. Martins, 3D and VR models in Civil Engineering education: Construction, rehabilitation and maintenance, Automation in Construction. 19 (2010) pp. 819–828. https://doi.org/10.1016/j.autcon.2010.05.006.

[98] A.H. Behzadan, V.R. Kamat, Enabling discovery-based learning in construction using telepresent augmented reality, Automation in Construction. 33 (2013) pp. 3–10. https://doi.org/10.1016/j.autcon.2012.09.003.

[99] S.S. Sørensen, Augmented Reality for Improved Communication of Construction and Maintenance Plans in Nuclear Power Plants, Progress of Nuclear Safety for Symbiosis and Sustainability, Springer Japan, Tokyo, 2014: pp. 269–274. https://doi.org/10.1007/978-4-431-54610-8_27.

[100] J. Wang, L. Hou, Y. Wang, X. Wang, I. Simpson, Integrating Augmented Reality into Building Information Modeling for Facility Management Case Studies, Building Information Modeling, American Society of Civil Engineers, Reston, VA, 2015: pp. 279–304. https://doi.org/10.1061/9780784413982.ch11.

[101] C. Fu, G. Aouad, A. Lee, A. Mashall-Ponting, S. Wu, IFC model viewer to support nD model application, Automation in Construction. 15 (2006) pp. 178–185. https://doi.org/10.1016/j.autcon.2005.04.002.

[102] S. Côté, M. Beauvais, A. Girard-Vallée, R. Snyder, A live Augmented Reality Tool for Facilitating Interpretation of 2D Construction Drawings, Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), Springer, 2014 pp. 421–427. https://doi.org/10.1007/978-3-319-13969-2_32.

[103] S. Wang, Application of BIM and VR technology in complex construction project: A case study of iceberg 3d BIM structure layout design for an ocean park, Communications in Computer and Information Science. 369 CCIS (2013) pp. 245–255. https://doi.org/10.1007/978-3-642-38974-0_23.

[104] A.Z. Sampaio, 4D/BIM model linked to VR technology, ACM International Conference Proceeding Series. (2017). https://doi.org/10.1145/3110292.3110298.

[105] R. Charef, H. Alaka, S. Emmitt, Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views, Journal of Building Engineering. 19 (2018) pp. 242–257. https://doi.org/10.1016/j.jobe.2018.04.028.

[106] F.J. Montiel-Santiago, M.J. Hermoso-Orzáez, J. Terrados-Cepeda, Sustainability and Energy Efficiency: BIM 6D. Study of the BIM Methodology Applied to Hospital Buildings. Value of Interior Lighting and Daylight in Energy Simulation, Sustainability. 12 (2020) 5731. https://doi.org/10.3390/su12145731.

[107] I. Kamardeen, 8D BIM modelling tool for accident prevention through design, Association of Researchers in Construction Management, Proceedings of the 26th Annual Conference on Association of Researchers in Construction Management. (2010) pp. 281–289. https://www.arcom.ac.uk/-docs/proceedings/ar2010-0281-0289_Kamardeen.pdf (accessed October 19, 2021).

[108] I.B. Kjartansdóttir, S. Mordue, P. Nowak, D. Philp, J. T. Snæbjörnsson, Building information modelling – BIM, Civil Engineering Faculty of Warsaw University of Technology, 2017 (ISBN8394792073, 9788394792077).

[109] W. Zhou, J. Tah, D. Heesom, A Distributed Virtual Reality Application Framework for Collaborative Construction Planning using BIM server, Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, London, UK. (2013) pp. 458–467. https://itc.scix.net/pdfs/convr-2013-46.pdf (accessed October 19, 2021).

[110] K. Kuncham, Timelining The Construction in Immersive Virtual Reality System Using BIM Application, oaktrust.library.tamu.edu, 2013. https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/151003/KUNCHAM-THESIS-2013.pdf?sequence=1&isAllowed=y (accessed October 19, 2021).

[111] J. Pan, Applications of augmented reality during construction stage, ira.lib.polyu.edu.hk, 2011. https://theses.lib.polyu.edu.hk/bitstream/200/6197/1/b24562178.pdf (accessed October 19, 2021).

[112] M.G. Fard, 4-Dimensional Augmented Reality-Models For Automation And Interactive Visualization Of Construction Progress Monitoring, Doctoral dissertation, 2010. http://hdl.handle.net/2142/33766 (accessed October 19, 2021).

[113] Hyeon-seung Kim, Chang-hak Kim, Hyoun-seok Moon, So-yeong Moon, Young-hwan Kim, L. Kang, Application of augmented reality object in construction project, 3rd World Congress on Information and Communication Technologies (WICT 2013), IEEE, 2013 pp. 117–120. https://doi.org/10.1109/WICT.2013.7113121.

[114] A.R. Singh, V. Suthar, V.S.K. Delhi, Augmented Reality (AR) Based Approach to Achieve an Optimal Site Layout in Construction Projects, Proceedings of the 34th International Symposium on Automation and Robotics in Construction, ISARC 2017 pp. 165–172. https://doi.org/10.22260/ISARC2017/0022.

[115] A. Schweigkofler, G.P. Monizza, E. Domi, A. Popescu, J. Ratajczak, C. Marcher, M. Riedl, D. Matt, Development of a Digital Platform Based on the Integration of Augmented Reality and BIM for the Management of Information in Construction Processes, IFIP Advances in Information and Communication Technology, Springer, 2018 pp. 46–55. https://doi.org/10.1007/978-3-030-01614-2_5.

[116] J. Chalhoub, Benefits of Using Augmented Reality in Planning, Construction and Post-Construction Phases in Specialty Contracting, Doctoral dissertation, 2019. https://repository.asu.edu/attachments/216614/content/Chalhoub_asu_0010E_18636.pdf (accessed October 19, 2021).

[117] J. Lucas, Immersive VR in the construction classroom to increase student understanding of sequence, assembly, and space of wood frame construction, Journal of Information Technology in Construction. 23 (2018) pp. 179–194. https://itcon.org/papers/2018_09-ITcon-Lucas.pdf (accessed October 19, 2021).

[118] T.K. Wang, J. Huang, P.C. Liao, Y. Piao, Does Augmented Reality Effectively Foster Visual Learning Process in Construction? An Eye-Tracking Study in Steel Installation, Advances in Civil Engineering. 2018 (2018) pp. 1–12. https://doi.org/10.1155/2018/2472167.

[119] A.R.M. Cuperschmid, M.G. Grachet, M.M. Fabrício, Development of an Augmented Reality environment for the assembly of a precast wood-frame wall using the BIM model, Ambiente Construído. 16 (2016) pp. 63–78. https://doi.org/10.1590/s1678-86212016000400105.

[120] C. Kwiatek, M. Sharif, S. Li, C. Haas, S. Walbridge, Impact of augmented reality and spatial cognition on assembly in construction, Automation in Construction. 108 (2019) 102935. https://doi.org/10.1016/j.autcon.2019.102935.

[121] A. Pedro, C.S. Park, A Construction Safety Education System Based on Interactive Virtual Reality, Proceedings for the CIB W099 Achieving Sustainable Construction Health and Safety 2014 pp. 494–504. https://portal.research.lu.se/en/publications/proceedings-for-the-cib-w099-achieving-sustainable-construction-h (accessed October 19, 2021).

[122] Q. Le, A. Pedro, C. Lim, H. Park, C. Park, H. Kim, A framework for using mobile based virtual reality and augmented reality for experiential construction safety education, The International Journal of Engineering Education. 31 (2015) pp. 713–725. https://www.semanticscholar.org/paper/A-framework-for-using-mobile-based-virtual-reality-Le-Pedro/9194ce038cf5440e1faecc034d401241458738b6 (accessed October 19, 2021).

[123] A. Pedro, Q.T. Le, C.S. Park, Framework for Integrating Safety into Construction Methods Education through Interactive Virtual Reality, Journal of Professional Issues in Engineering Education and Practice. 142 (2016) 04015011. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000261.

[124] H.C. Pham, N.N. Dao, A. Pedro, Q.T. Le, R. Hussain, S. Cho, C.S. Park, Virtual field trip for mobile construction safety education using 360-degree panoramic virtual reality, International Journal of Engineering Education. 34 (2018) 1174–1191. https://www.semanticscholar.org/paper/Virtual-field-trip-for-mobile-construction-safety-Pham-Dao/f941c9ef5662a68cb94998523ef864f1f10e5fc0 (accessed October 19, 2021).

[125] A. Perlman, R. Sacks, R. Barak, Hazard recognition and risk perception in construction, Safety Science. 64 (2014) pp. 22–31. https://doi.org/10.1016/j.ssci.2013.11.019.

[126] H. Xie, W. Shi, R.R.A. Issa, Using rfid and real-time virtual reality simulation for optimization in steel construction, Electronic Journal of Information Technology in Construction. 16 (2011) pp. 291–308. https://www.itcon.org/paper/2011/19 (accessed October 19, 2021).

[127] H. Bae, M. Golparvar-Fard, J. White, High-precision vision-based mobile augmented reality system for context-aware architectural, engineering, construction and facility management (AEC/FM) applications, Visualization in Engineering. 1 (2013) 3. https://doi.org/10.1186/2213-7459-1-3.

[128] T.-H. Lin, C.-H. Liu, M.-H. Tsai, S.-C. Kang, Using Augmented Reality in a Multiscreen Environment for Construction Discussion, Journal of Computing in Civil Engineering. 29 (2015) 04014088. https://doi.org/10.1061/(asce)cp.1943-5487.0000420.

[129] F. Chionna, F. Argese, V. Palmieri, I. Spada, L. Colizzi, Integrating building information modeling and augmented reality to improve investigation of historical buildings, Conservation Science in Cultural Heritage. 15 (2015) pp. 133–148. https://doi.org/10.6092/issn.1973-9494/6174.

[130] J. Du, Y. Shi, C. Mei, J. Quarles, W. Yan, Communication by Interaction: A Multiplayer VR Environment for Building Walkthroughs, Construction Research Congress 2016, American Society of Civil Engineers, Reston, VA, 2016 pp. 2281–2290. https://doi.org/10.1061/9780784479827.227.

[131] T. Hilfert, M. König, Low-cost virtual reality environment for engineering and construction, Visualization in Engineering. 4 (2016) 2. https://doi.org/10.1186/s40327-015-0031-5.

[132] A. Motamedi, Z. Wang, N. Yabuki, T. Fukuda, T. Michikawa, Signage visibility analysis and optimization system using BIM-enabled virtual reality (VR) environments, Advanced Engineering Informatics. 32 (2017) pp. 248–262. https://doi.org/10.1016/j.aei.2017.03.005.

[133] J. Ratajczak, A. Schweigkofler, M. Riedl, D.T. Matt, Augmented Reality Combined with Location-Based Management System to Improve the Construction Process, Quality Control and Information Flow, Advances in Informatics and Computing in Civil and Construction Engineering. 35 (2018) pp. 289–296. https://doi.org/10.1007/978-3-030-00220-6_35.

[134] J. Du, Z. Zou, Y. Shi, D. Zhao, Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making, Automation in Construction. 85 (2018) pp. 51–64. https://doi.org/10.1016/j.autcon.2017.10.009.

[135] A. Ganiev, H. Sun Shin, K. Hee Lee, Implementation of Online and Offline Building Information System based on Virtual Reality and Augmented Reality, International Journal of Engineering & Technology. 7 (2018) 37. https://doi.org/10.14419/ijet.v7i3.33.18519.

[136] G. Ozcan-Deniz, Towards a BIM-based System Integrated to a Virtual Reality Platform, Tamap Journal of Engineering. 2018 (2019). https://doi.org/10.29371/2018.3.62.

[137] S. Vincke, R. de Lima Hernandez, M. Bassier, M. Vergauwen, Immersive Visualisation Of Construction Site Point Cloud Data, Meshes And BIM Models In A VR Environment Using A Gaming Engine, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. XLII-5/W2 (2019) pp. 77–83. https://doi.org/10.5194/isprs-archives-XLII-5-W2-77-2019.

[138] P. Tavares, C.M. Costa, L. Rocha, P. Malaca, P. Costa, A.P. Moreira, A. Sousa, G. Veiga, Collaborative Welding System using BIM for Robotic Reprogramming and Spatial Augmented Reality, Automation in Construction. 106 (2019) 102825. https://doi.org/10.1016/j.autcon.2019.04.020.

[139] B. Dalton, M. Parfitt, Immersive Visualization of Building Information Models, Working Paper, 2013. http://www.reading.ac.uk/web/files/designinnovation/DIRC_Working_Paper_6.pdf (accessed October 19, 2021).

[140] P. Chevaillier, T.-H. Trinh, M. Barange, P. de Loor, F. Devillers, J. Soler, R. Querrec, Semantic modeling of Virtual Environments using MASCARET, 5th Workshop on Software Engineering and Architectures for Realtime Interactive Systems (SEARIS), IEEE, 2012 pp. 1–8. https://doi.org/10.1109/SEARIS.2012.6231174.

[141] G. Claude, V. Gouranton, R. Bouville Berthelot, B. Arnaldi, Short paper: #Seven, a sensor effector based scenarios model for driving collaborative virtual environment, International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments, ICAT-EGVE 2014, 2019. https://doi.org/10.2312/ve.20141366.

[142] V. Lanquepin, K. Carpentier, D. Lourdeaux, M. Lhommet, C. Barot, K. Amokrane, HUMANS, Proceedings of the Virtual Reality International Conference: Laval Virtual, ACM, New York, NY, USA, 2013: pp. 1–8. https://doi.org/10.1145/2466816.2466826.

[143] M. Dragoni, C. Ghidini, P. Busetta, M. Fruet, M. Pedrotti, Using Ontologies for Modeling Virtual Reality Scenarios, in: Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 2015: pp. 575–590. https://doi.org/10.1007/978-3-319-18818-8_35.

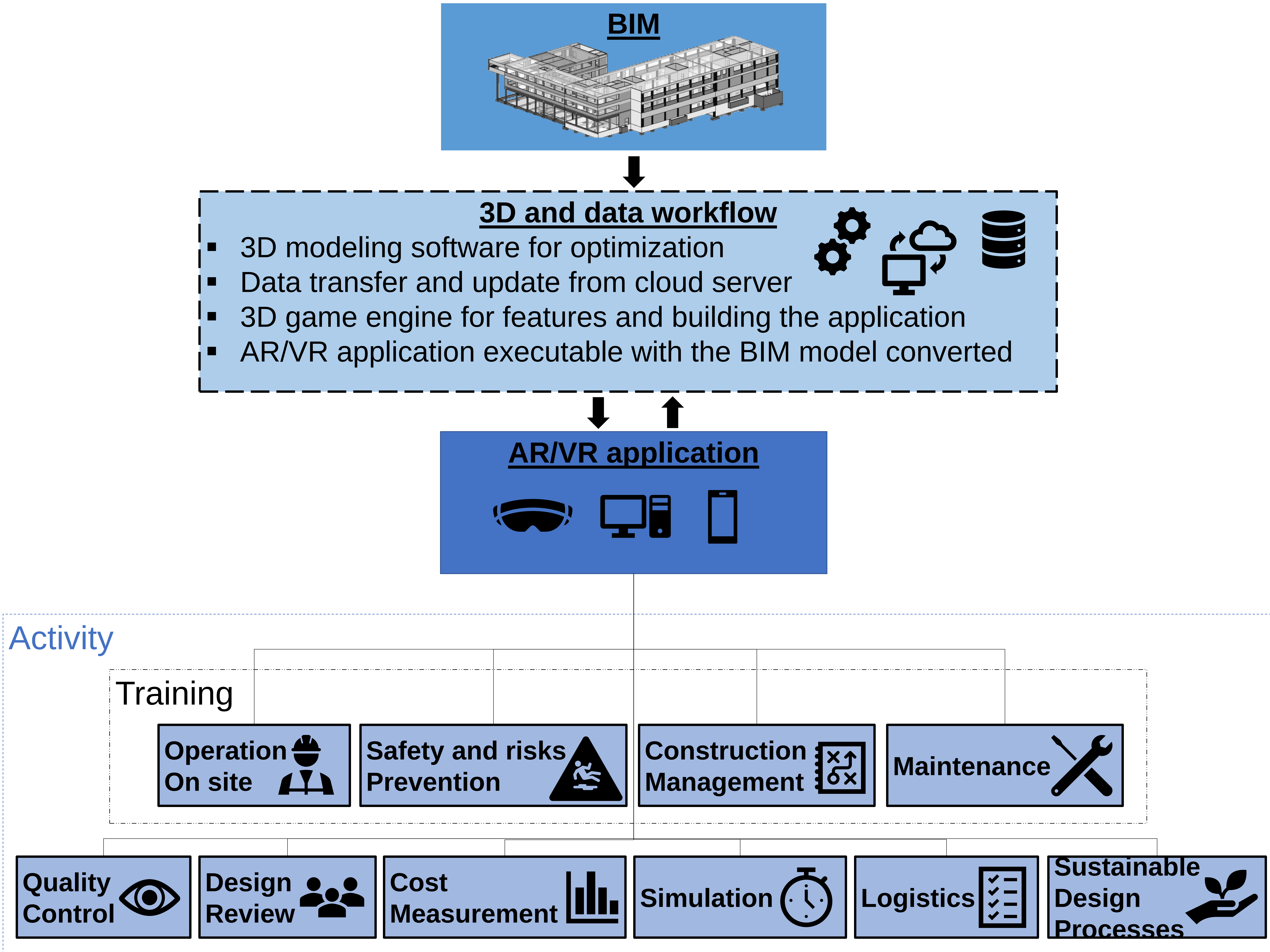
[144] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic Construction Digital Twin: Directions for future research, Automation in Construction. 114 (2020) 103179. https://doi.org/10.1016/j.autcon.2020.103179.

[145] L. Zhang, R.R.A. Issa, Development of IFC-based construction industry ontology for information retrieval from IFC models, EG-ICE 2011, European Group for Intelligent Computing in Engineering. (2014). http://www.proceedings.com/24293.html (accessed October 19, 2021).

[146] P. Pauwels, W. Terkaj, EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Automation in Construction. 63 (2016) pp. 100–133. https://doi.org/10.1016/j.autcon.2015.12.003.

[147] S. Zhang, F. Boukamp, J. Teizer, Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA), Automation in Construction. 52 (2015) pp. 29–41. https://doi.org/10.1016/j.autcon.2015.02.005.

[148] V. Havard, B. Jeanne, X. Savatier, D. Baudry, Inoovas - Industrial ontology for operation in virtual and augmented scene: The architecture, 2017 4th International Conference on Control, Decision and Information Technologies (CoDIT), IEEE, 2017 pp. 0300–0305. https://doi.org/10.1109/CoDIT.2017.8102608.



BIM
3D and data workflow
3D modeling software for optimization
Data transfer and update from cloud server
3D game engine for features and building the application
AR/VR application executable with the BIM model converted
AR/VR application
Activity
Training
Operation On site
Safety and risks Prevention
Construction Management
Maintenance
Quality Control
Design Review
Cost Measurement
Simulation
Logistics
Sustainable Design Processes