Frameworks and Processes for VR integration in AEC project management

Report presented by

Merwane Zioui

For the Master 1 MIAGE degree

From Université Paris 1 Panthéon-Sorbonne

Academic year: *2022-2023*

Date of defense: *07/05/23*

Thesis director: *Daniel Diaz*

Jury members: *Nourhène Ben Rabah*, *Daniel Diaz*

Acknowledgements

First of all, I would like to thank my thesis supervisor, Mr Daniel Diaz, for his advice and the time he gave me to write this document. His advice enabled me to deepen my thinking and apply the best possible practices.

I would also like to thank the members of the teaching staff at Université Paris 1 Panthéon-Sorbonne, for the practical and theoretical knowledge they provided during my 2 years in MIAGE.

Abstract

The aim of this state of the art is to present the various applications that can be made of virtual reality (VR) in the field of construction and civil engineering. With the democratization of this technology and its use in various industries, it is important to study possible ways of implementing the technology in strategic areas closely linked to the quality of life of the inhabitants. Thus, the study focuses on 3 axes corresponding to different phases of a project: the uses related to collaboration, the uses for the design of infrastructure, and the uses for the planning of projects.

Keywords: AEC, BIM, Virtual Reality, Collaboration, Construction, Modeling, Construction planning, Communication, Design, Simulation

Abstract (French)

Cet état de l’art a pour but de présenter les différentes applications pouvant être faites de la réalité virtuelle (VR) dans le domaine de la construction et du génie civil. Avec la démocratisation de cette technologie et l’utilisation de celle-ci dans diverses industries, il est important d’étudier les axes possibles d’implémentation de la technologie dans des domaines stratégiques et étroitement liés à la qualité de vie des habitants. Ainsi, l’étude se concentre sur 3 axes correspondant à différentes phases d’un projet : les usages liés à la collaboration, les usages pour la conception d’infrastructures, et les usages pour la planification des projets.

Mots-clés : AEC, BIM, Réalité virtuelle, Collaboration, Construction, Modélisation, Planification de la construction, Communication, Design, Simulation

Table of contents

Introduction

The evolution of digital technology in recent years is transforming various sectors worldwide, including the building industry, usually seen as slow to adopt revolutionary technologies. However, a reversal is underway with the adoption of emerging technologies such as Building Information Modeling (BIM), the Internet of Things(IoT), or Virtual Reality (VR) more recently. In particular, this tech opens new borders in the way development projects are conceptualized, planned and executed.

The early stages of construction projects (pre-design, design, planning) are crucial because they lay the foundation for all subsequent stages of a project. These stages require coordination and collaboration between task actors, such as architects, engineers, contractors and finish customers. However, this cooperation can often be sophisticated, given the different professional languages, or even the physical obstacles we have experienced during the pandemic. This requires innovative methods that facilitate more effective collaboration, thus reducing errors, mistakes and modifications later in the project life cycle, generating extra costs.

Virtual reality, with its potential to create engaging 3D environments, offers unique opportunities to improve collaboration during these earlier phases of construction. The technology allows stakeholders to imagine, socialize and manipulate proposed designs in a simulated space, improving communication, reducing ambiguity and improving shared decision - making. The position and effect of VR in enhancing collaboration in the early stages of development projects are not yet fully understood or documented, despite the apparent potential.

Therefore, this essay aims to provide an answer to the following query: "**How can VR enhance the preliminary stages of construction projects from a collaborative perspective?**" The aim of this document is to collect, analyze and synthesize recent advances in books, based on experiments, conceptual articles and study cases exploring the application of VR in the first phases of construction projects, while focusing on cooperative aspects. It identifies constraints, offers a better understanding of the state of knowledge at the moment, and makes an effort to suggest potential research directions for the future.

By providing a critical evaluation of the existing literature on the subject, this paper may offer useful information to stars in the field, from experts to practitioners. By emphasizing the potential of VR as a collaborative tool in the early stages of development projects, it aims to add to the ongoing discussion about the digital transition of the building industry. In this way, the results of this review will show potential areas for VR advancement and future implementation in addition to shedding light on the current state of construction applications.

Background

AEC

In a construction project, Architecture, Engineering, and Construction (AEC) is an acronym representing the expertise of multiple professionals ensuring the good delivery, and quality of a building, from every stackholders' point of view.

Building Information Modeling (BIM)

Building Information Modeling (BIM) is a practice used in the construction industry to represent buildings and their characteristics in a digital format. It serves as a shared understanding resource for information about a service, forming a trustworthy basis for choices during its life cycle. BIM is a process that involves the generation and management of physical and functional traits of infrastructures. The team members' input is gathered through this process to help model components and tools used later in the construction phases.

Beyond building drawings, BIM software offers a model-based approach to designing and managing buildings and infrastructures, allowing users to digitally represent the useful characteristics of edifices. Autodesk Revit, ArchiCAD, SketchUp, Rhino, Vectorworks, Plannerly, Trimble Connect, Revizto, and BIMCollab are a few of the most well-used BIM tools. These tools offer a variety of functions, including 3D modeling, documentation and collaboration.

The benefits of BIM extend beyond the style stage, providing value through a project. It allows for more accurate and efficient creating design, improved modeling, better cooperation, and enhanced conversation. In addition to other advantages, BIM enables automatic generation of architecture paperwork, increased productivity due to simple information retrieval, and improved coordination of construction documents.

Virtual Reality (VR)

With the use of virtual reality (VR) technology, users may explore and interact with a simulated 3D environment in a way that closely resembles reality. Computer hardware and software were used to construct this environment, and users may also need to employ accessories like headsets to interact with it. Users can become more fully immersed in a VR world.

Non-immersive, partially-immersive, and fully-immersive are the three basic categories of VR. Non-immersive virtual reality (VR) describes a 3D simulated environment that is accessed through a computer screen and can be partially controlled by the user using a keyboard, mouse, or other device. Semi-immersive VR focuses primarily on the visual 3D portion of virtual reality and provides a partial virtual experience that can be accessed through a computer screen, glasses, or headset. The highest level of virtual reality is delivered by fully immersive VR, which entirely submerges the user in the created 3D world. It includes hearing, seeing, and occasionally touching.

Through the use of VR headsets like the Oculus Rift or HTC Vive, users using software like BIMXplorer in the fields of architecture, engineering, and construction can import a BIM model and navigate a 3D model of a building as if they were playing a video game. This usage of VR technology can be especially beneficial for picturing intricate construction designs and comprehending how various building components would interact in a real-world setting.

Methodology of research

While developing this paper, a rigorous research methodology was implemented to ensure comprehensive and relevant coverage of the subject. Initially, a query was conducted to gather a set of 108 articles through an institutional tool called MIAGE Scholar. This tool, developed by internals of the University of Paris 1 Panthéon-Sorbonne, allows users to search papers through multiple types of data sources (Open Access, Paywall, Google Scholar). The following query was given to the search engine:

(TITLE-ABS-KEY("building information modeling") OR TITLE-ABS-KEY("civil information modeling") OR TITLE-ABS-KEY("smart city design")) AND (TITLE("virtual reality") OR TITLE("metaverse"))

The search was made via multiple keywords directly related to the subject of this paper, and additional ones such as "smart city design" and "metaverse", to ensure some articles with new vocabulary could be captured by the query. As the topic is clearly mentioned in recent literature only, there was no need to specify a publication date in the prompt. From this initial query, the workflow used for the writing of this review is presented on Figure 1:

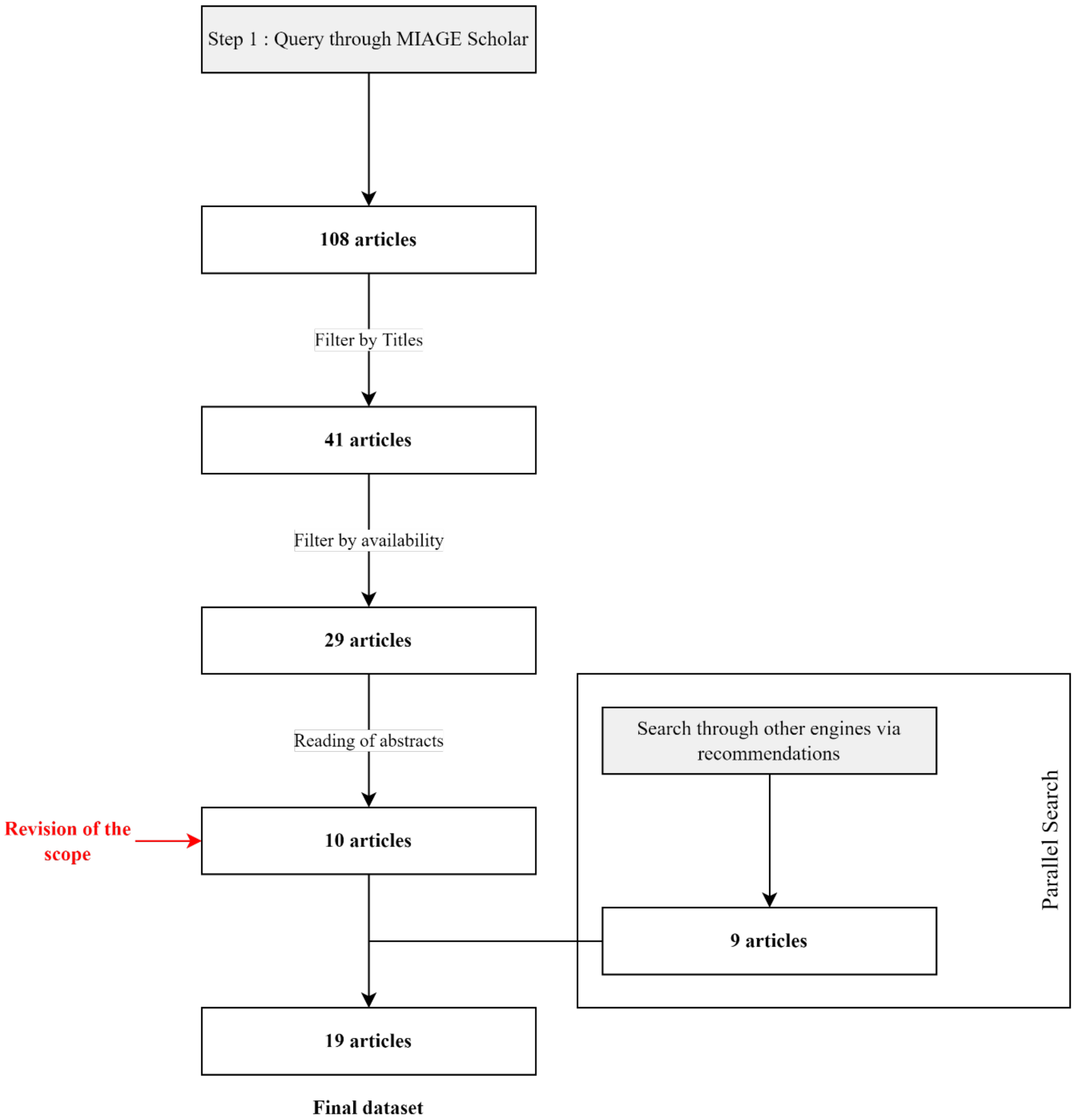

Figure 1 - Applied methodology

These articles were then subjected to an evaluation of their relevance based on their title, allowing for the targeting of those directly related to the research topic. Subsequently, the accessibility of each article was verified, taking into account their availability in open access, via an institutional address, or through a paywall. To further refine the selection, the abstracts of the articles were read, allowing for the filtering of articles based on their specific relevance.

In parallel, an exploration of the references cited in these articles was conducted, as well as the consultation of recommendations on the Research Gate platform, thereby broadening the scope of the research. Using another platform was necessary to provide the state of the art with more data, while being able to have similar/complimentary papers to present.

Following a modification of the research problem, a revision of the article selection was necessary, resulting in the elimination of those that no longer corresponded to the subject. There was no need to restart the entire process, as scope was only reduced.

At the end of this process, 19 references were retained, thus constituting the state of the art on the subject. These references provide a solid foundation for further analysis and discussion within the framework of this thesis.

After retrieving the final dataset for this paper, the next step was to classify the articles by RQs (research questions). This method allowed me to have a better understanding of topics discussed in each article, and subsequently, classify them in each part of this paper. As a final result, I could draw a table with the parts where each article could be used in this document (Table 1).

Article #	**Construction planning**		**Collaboration**	**Conception**	
	Analysis	**Planning**		**Simulation**	**Design**
[1]			X		
[2]			X		
[3]			X		
[4]			X		
[5]				X	
[6]				X	
[7]				X	
[8]	X		X		
[9]	X				
[10]	X				
[11]			X		X
[12]			X		
[13]	X		X		X
[14]			X		
[15]	X		X		
[16]		X			
[17]			X	X	X
[18]		X			
[19]		X			

Table 1-Cross references of articles

State of the art

Collaboration

Effective teamwork and smooth communication are essential for success in the dynamic world of construction projects. The Architecture, Engineering, and Construction (AEC) sector succeeds from the combined efforts of several stakeholders who cooperate to realize ambitious objectives. Traditional collaboration techniques, however, frequently run into issues that reduce productivity and make it harder to achieve project objectives. The requirement for physical presence, the lack of fully immersive model representation, and workflow complexity are some of these difficulties.

In this setting, the use of Virtual Reality (VR) technology stands out as a potentially game-changing innovation, enabling creative answers to change collaboration and communication in building projects. VR has the potential to lower barriers, optimize processes, and improve communication by immersing stakeholders in interactive, realistic virtual environments. The road to mainstream VR adoption in the AEC industry is not without challenges, though. Significant obstacles must be overcome due to high implementation costs, reluctance to change, and the requirement for technical skills. The experiments, technical solutions, and findings that shed light on the potential and challenges of integrating VR into the AEC workflow are explored in this section, which digs into the contributions of VR for collaboration and communication in construction projects.

On the one hand, traditional Building Information Modeling (BIM) techniques are stated to have limits, whereas VR is said to provide a ground-breaking answer. VR outperforms traditional 2D or 3D screens by incorporating head-mounted displays (HMDs), allowing for a more immersive interaction with 3D models [10]. The capacity of this immersive experience to create a realistic and collaborative environment that improves stakeholders' knowledge of complex construction projects has been praised [12]. Furthermore, experiments using VR technology have demonstrated its effectiveness in addressing practical challenges, such as accessing MEP[1] elements for repair and replacement in building systems maintenance. These experiments have simulated real-world scenarios, providing valuable insights into the potential of VR to overcome such obstacles [10].

The viability and practicality of using VR technology in the AEC sector, however, are questioned by doubters. The complicated workflow required to convert a Revit model to a VR environment has caused participants in several tests to express concerns [10]. These worries draw attention to potential roadblocks that might prevent the seamless incorporation of VR into current AEC operations. Additionally, a major obstacle to mainstream adoption of VR technology is its high implementation costs [10]. The cost of purchasing VR hardware, software, and training materials can be expensive, which limits the industry's capacity to scale up VR solutions.

[1] Mechanical, Electrical, Plumbing. These refer to multiple components in a building such as heating and cooling systems (Mechanical), providing electricity (Electrical), and water supply of the building (Plumbing) [23].

However, academics have worked to reduce these issues and improve VR systems to suit the particular requirements of the AEC industry. CoVR and other collaborative VR systems have been created to make it easier for different stakeholders in construction projects to communicate and work together [11]. The CoVR system has several layers that work together to speed up collaboration, including a BIM layer, a middleware layer, a game engine layer, and a cloud networking layer (Figure 2) [11]. This innovative strategy shows an effort to close the gap between conventional procedures and VR technologies.

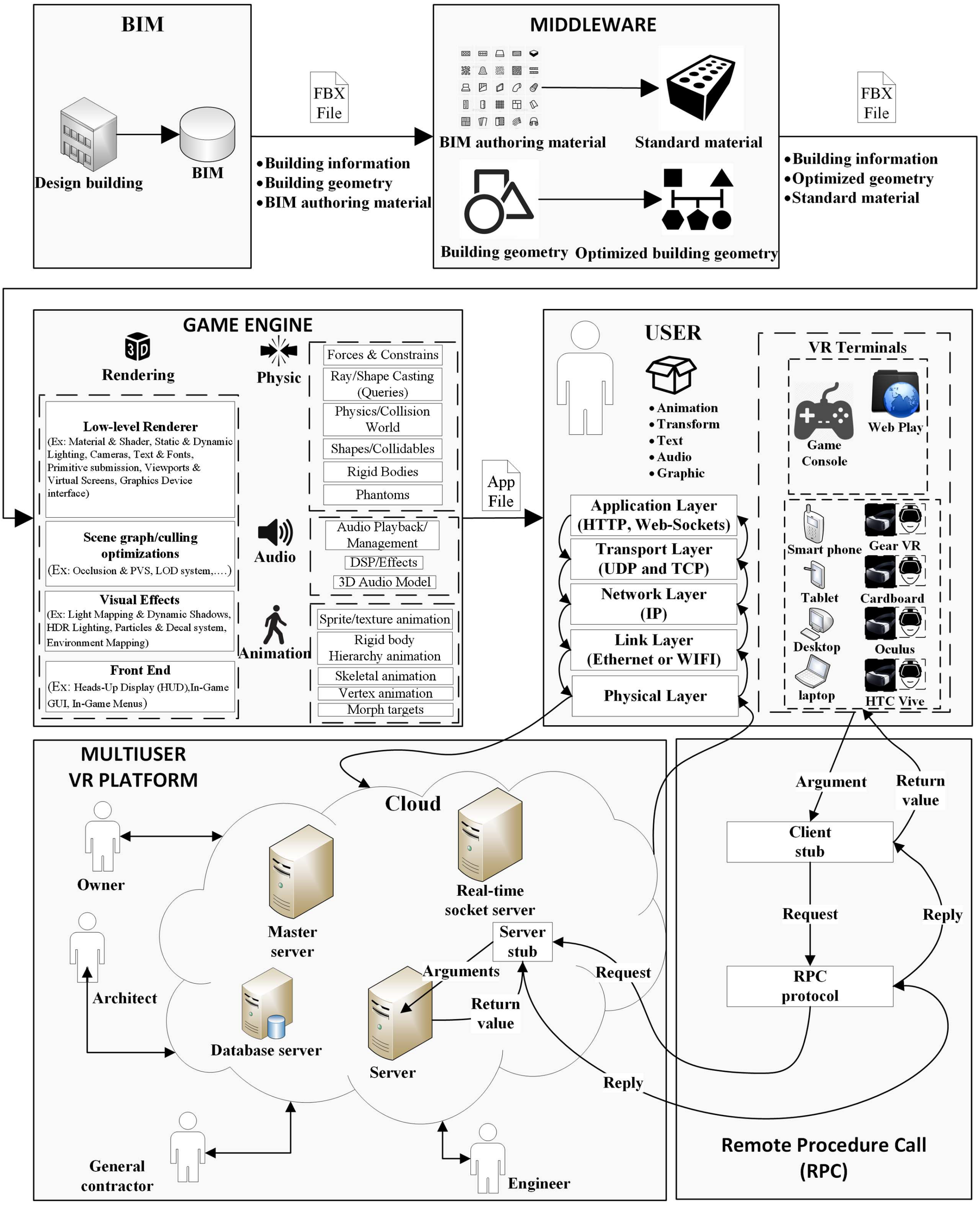

Figure 2-Layer approach used for CoVR [11]

Additionally, CoVR experiments have produced promising results. The usefulness of the collaboration made possible by the system was highlighted by the fact that participants who interacted in the VR environment found a substantially higher number of differences between virtual models and actual buildings [11]. This demonstrates how VR may enhance stakeholder decision-making and communication in construction projects.

Similar to this, the BIMXplorer VR system has been used in actual projects to investigate the advantages of VR in a context focused on construction [12]. The system's features have been praised for their potential to improve project planning, review, and constructability analysis, such as direct import of Industry Foundation Classes[2] (IFC) files and complete visualization tools [12]. Although some critics claim that VR excels in these areas, they assert that off-the-shelf BIM-to-VR technologies frequently lack full integration or the essential adaptability for varied AEC applications [11].

In conclusion, the adoption of VR technology in the AEC sector has the potential to revolutionize current methods of communication and cooperation. However, challenges such as workflow complexities, high implementation costs, and the need for customization and technical knowledge must be addressed to ensure the successful and widespread adoption of VR in the industry [10][11]. To overcome these obstacles and realize the full potential of VR for collaboration and communication in building projects, additional study, stakeholder feedback, and iterative system improvements are required [10][11][12].

Data integration

Due primarily to efficient data integration, Virtual Reality (VR) has an undeniable impact on collaboration and communication in a building project. The Building Virtual Reality System (BVRS) [14] and an application for the automated integration of 4D models in VR environments [15] are two cutting-edge systems that use VR to promote collaboration and improve data integration in the Architecture, Engineering, and Construction (AEC) industry. Data integration is one of the challenges that can greatly increase productivity and collaboration, enabling people to exchange information easily throughout the project.

[2] IFC is a standard used in the construction industry to describe buildings specifications, relationships, objects, and processes [25].

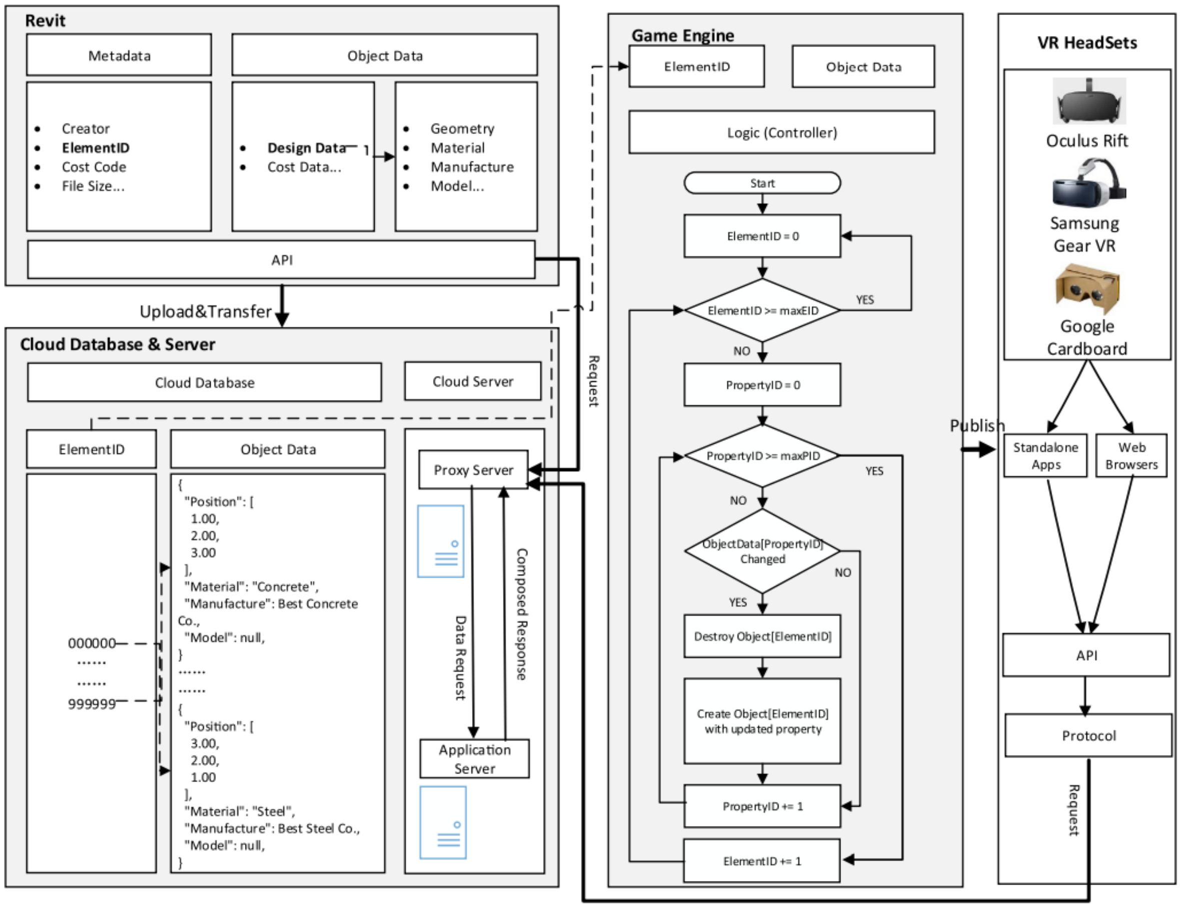

Fig. 1. Architecture of BVRS.

Figure 3-Components architecture used by BVRS [14]

In order to provide real-time data synchronization between Building Information Modelling (BIM) and VR applications, BVRS first adopts a robust approach (Figure 3). The collection of specific metadata from BIM software, such as Global Unique Identifier (GUID), Unique ID, and Element ID, allows for this synchronization. Real-time data synchronization is therefore made possible by the resulting transmission of these metadata to a cloud server via HTTP or HTTPS protocols [14]. On the other hand, the 4D program begins by importing a 3D model from Revit in the FBX format, which is compatible with Unity 3D. To preserve the texture rendering in Unity 3D, this method requires importing the Revit model into 3DSMax first before exporting it in FBX format [15]. These procedures show various methods for data integration.

Another essential component for improving user interaction with the virtual environment is the user interface. BVRS creates a user interface specifically for the kind of VR headset being used. Through an avatar control system, it also enables users to move within the virtual environment with greater autonomy and supports real-time model updates [14]. The 4D system, in contrast, offers a straightforward user interface that contains a window showing the 4D model, a text box displaying the construction date, and buttons to change the date that is presented (Figure 4). The interface can only be partially projected in the VR world, and any changes require a new file export from Unity [15].

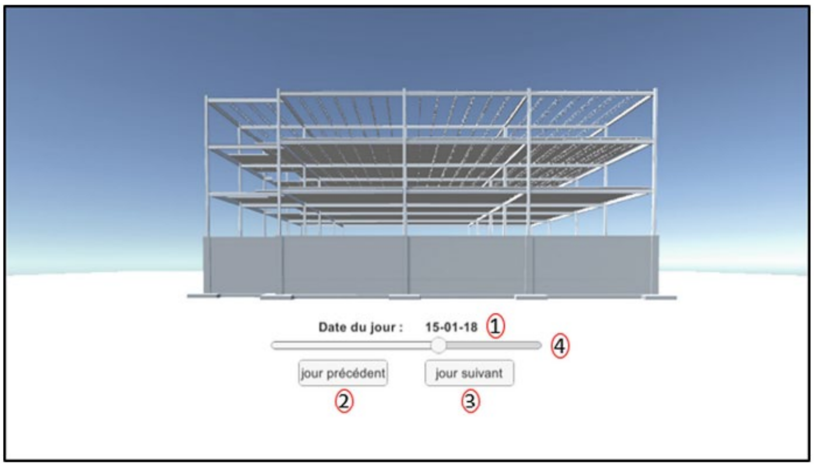

Fig. 4. User interface of the application (in French)

Figure 4-User interface of the 4D application [15]

The 4D application and BVRS employ various approaches for collaboration. By allowing numerous users to engage with the same BIM model in the VR area at once, BVRS proved its ability to promote collaborative work [14]. Although the 4D program supports collaboration, it doesn't say how it makes it possible to work together in a virtual environment [15].

The 4D application finds various opportunities for development in terms of data integration. For instance, it is suggested to optimize the data import procedure for both the 3D model and the construction schedule as well as to automate the coding of the imported schedule. Additionally, the adoption of a standard like Uniformat II may make it simpler to link the list of 3D items with the list of scheduled tasks [15]. Uniformat II is a classification system used in construction projects for specifications, analysis and cost estimation of buildings. On the other hand, BVRS exhibits improvement improvements in its data integration, particularly for the computation time required to synchronize and integrate more complicated models with numerous interdependencies [14].

In conclusion, while BVRS and the 4D application take slightly different approaches to facilitate collaboration and communication in the AEC sector, both demonstrate the importance of effective data integration in achieving these goals. The comparison of these two systems highlights the various methods through which VR can enhance collaboration and communication within the context of construction projects, largely through improved data integration. Both systems demonstrate the potential of VR to improve not just visualization but also collaboration and communication, which could have significant implications for the future of the construction industry.

Performance of communications

Virtual Reality enables new proceedings for enhancing collaboration in the workspace. However, it is important to note that organizations have always preferred to use more traditional ways of communication, such as Face to Face meetings for decision making, or using BIM for exchanging information between stakeholders, as communication throughout the construction phases is one of the keys to the delivery of the project, in terms of costs, quality, and delivery, as well as a tool for a better comprehension of challenges in case of problem solving.

Facing nowadays challenges such as remote meetings, or the difficulty to gather all stakeholders in a physical setting, papers are trying to assess the effectiveness of VR communications, compared to traditional communication systems (FtF and BIM-based exchanges).

A class experiment has been conducted to compare the effectiveness of VR communications [1]. The study ran the experiment on 2 groups of students, one undergoing FtF meeting, and the other one VR meeting, both on the same construction project (Figure 5). Students had to roleplay different types of stakeholders, with different knowledge on the project. Based on participants' knowledge of the situation, they had to go through a decision-making process.

Figure 5-Two settings used for the experiment [1]

After each session, communications have been assessed through different criteria, resulting in an overall similar experience with both communication systems, despite the lack of nonverbal communication during VR sessions. Understanding of the situation is important for decision making, but the effectiveness of communication is also important for project planning (Figure 6).

Table 9. Paired Samples Wilcoxon Test Results

	Communication-effectiveness Criteria				
	Quality of Discussion	Appropriateness	Richness	Openness	Accuracy
FtF Communication	4.06 (0.6) *	4.48 (0.56)	3.74 (0.64)	4.25 (0.56)	3.27 (0.86)
IVR-based Communication	4 (0.6)	4.03 (0.42)	3.81 (0.7)	3.93 (0.58)	3.79 (0.63)
P value	0.64	0.04	0.71	0.15	0.03

*Mean (Standard deviation)

Table 10. Paired Samples Wilcoxon Test Results, Discussion-quality Subcomponents

	Issue understanding	Knowledge sharing	Satisfactory solution	Discussion effectiveness
FtF Communication	4.25 (0.67)*	4.08 (0.71)	4 (0.78)	3.91 (0.65)
IVR-based Communication	4.37 (0.49)	3.79 (0.77)	4.04 (0.8)	3.79 (0.77)
P value	0.49	0.82	0.17	0.46

*Mean (Standard deviation)

Table 11. Paired Samples Wilcoxon Test Results, Communication Appropriateness Subcomponents

	Concentration on others	Concentration from others	Politeness to others	Politeness from others
FtF Communication	4.37 (0.82)*	4.5 (0.65)	4.37 (0.71)	4.33 (0.70)
IVR-based Communication	4.04 (0.80)	4.04 (0.69)	4.25 (0.6)	4.29 (0.55)
P value	0.55	0.01	0.81	0.59

*Mean (Standard deviation)

Figure 6-Communications efficiency table [1]

A research paper investigated the performance of construction students in detection of error during construction scheduling. Users of the VR solution compared to traditional 2D documentation were found to be more confident with the use of VR, independently of their knowledge of the tool [3].

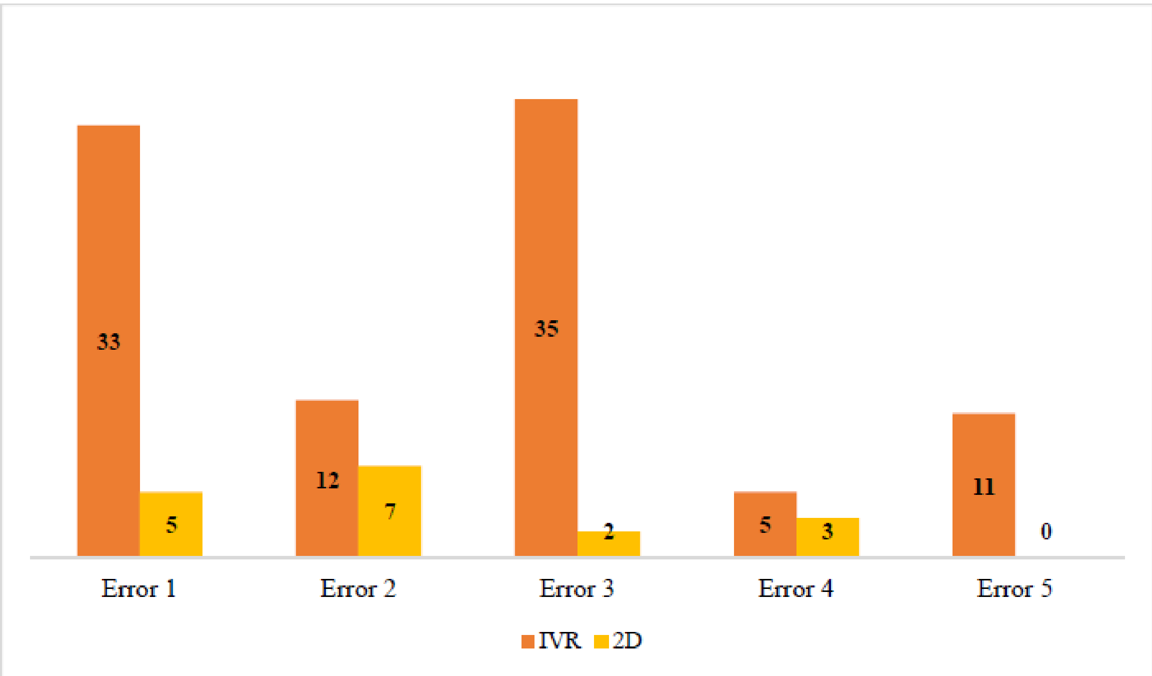

Figure 7-Task completion status (IVR vs. 2D) [3]

Communications were clearer, which led to less confusion, while building confidence in users' skills. Despite the lack of professional experience of some users, VR allowed each stakeholder to appropriate the different situations, acknowledging the data provided (architecture, annotations, design), to accelerate the decision process, and reduce the time needed share a common understanding of the assignment, by providing other sources of information that raw data (as compared to BIM exchanges between team members) [2]. Study [2] shows the pertinence of using VR rather than traditional BIM for creation and understanding of annotations regarding potential conflicts and errors on a 3D model. Two experiment groups are used, one performing tasks on BIM first then the VR system, and the other one with the opposite workflow, both in asynchronous and synchronous collaboration procedures (Figure 8).

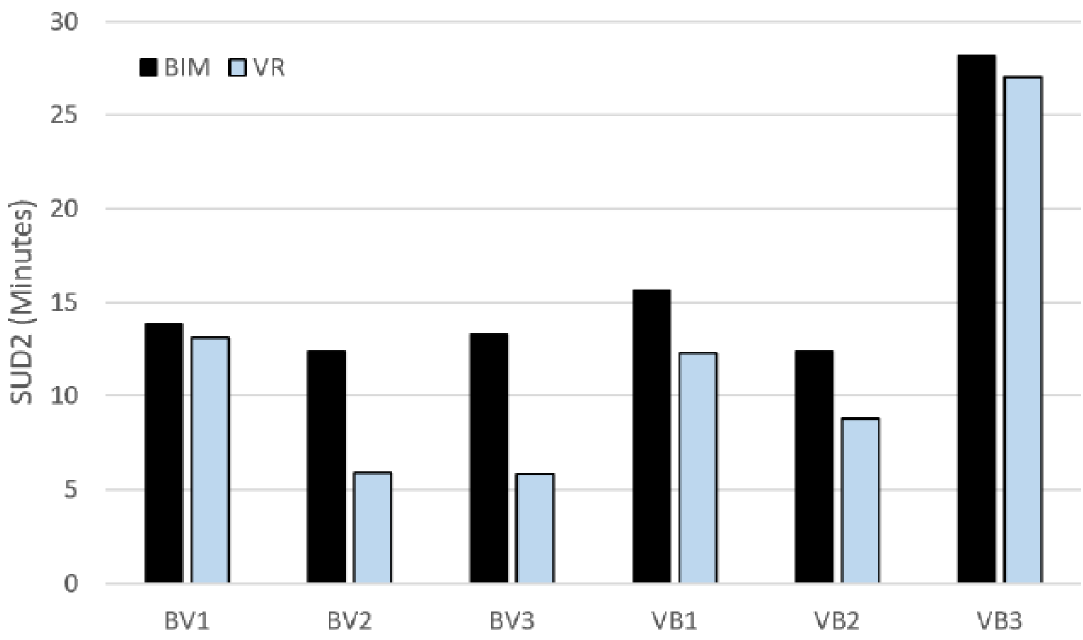

Figure 8-Time spent by each group in two platforms of BIM and VR to build Shared Understanding of the alternative design [2]

Even stakeholders outside of the organization such as clients can greatly improve their understanding of the building, leading to more qualitative exchanges and decision making [4]. These studies mentioned issues in the use of VR sessions for use cases, more relevant to the experience of users, such as physical discomfort [1], or the difficulty of imagining what the structure would look like in the real world [4].

Conception

Emergency simulation

Virtual Reality (VR) is increasingly being recognized as an important tool in the conceptual phase of building design, particularly within the Architecture, Engineering, and Construction (AEC) sector. As a building project, the infrastructure (private or public) has to follow rules ensuring clients' security, meaning an important phase of the project consists in various simulations. The significant advancements, particularly with the integration of foundational systems such as Oculus Rift and Leap Motion, provide innovative possibilities for visualization and interaction in modeled Virtual Environments (VEs) [6].

Performance-Based Earthquake Engineering (PBEE) is one area where VR is useful in building design. The Cave Automatic Virtual Environment (CAVE) of the MARquette

Visualization Laboratory was used in a pilot study by the Multi-Hazard Sustainability Research Group to illustrate an emergency reaction in the presence of strong earth movements. The system, which combined structural engineering, earthquake research, and building information modeling (BIM), allowed for the collection of site-specific ground vibrations that were used as seismic loads on the target structure [5].

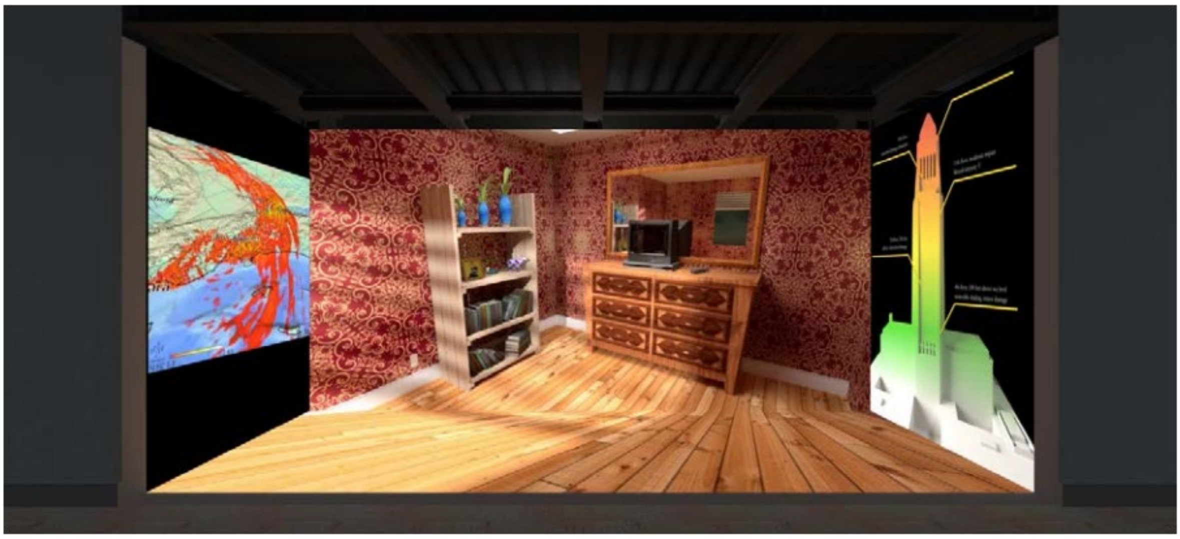

Figure 9-Illustrative CAVE visualization of SCEC MS earthquake simulations (left), responses of a structural model (right), an immerce space (center) [5]

The intensity of the ground vibrations used in this configuration is adjustable. The Performance-Based Earthquake Engineering (PBEE) methodology makes it easier to visualize emergency response in various ground motion scenarios. The Performance Assessment Calculation Tool (PACT), a component of the PBEE software package, offers fragility functions that estimate distributions of damage levels based on structural reactions [5].

VR also plays a significant role in evacuation testing and accessibility validation. VR environments, for instance, can be used to test multiple escape scenarios safely and with a realistic setup. Additionally, VR enables first-person testing of wheelchair accessibility, giving an angle that conventional techniques might not be able to. In evacuation testing, test operators can keep an eye on how signs indicating escape routes are seen subjectively and change the environment for following tests. The user's view angle can also be simultaneously recorded and kept for review and analysis in the future [6].

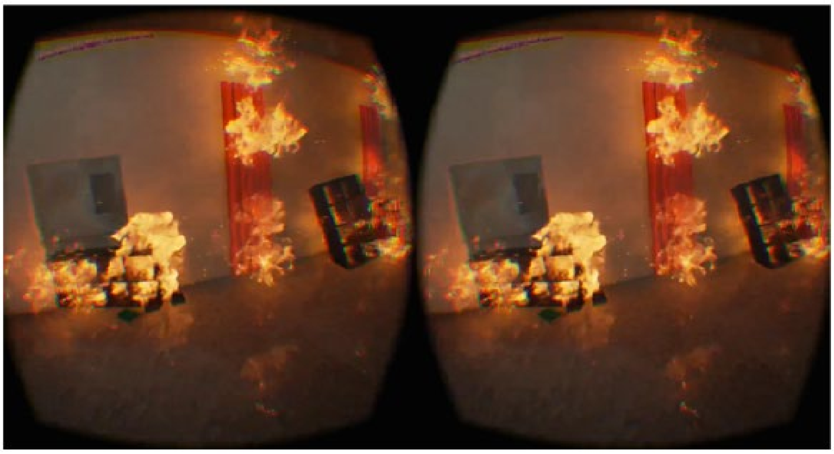

Figure 10-Realistic fire simulation with lighting [6]

In the case of accessibility validation, the additional hand detection and resulting arm placement enable a check for unreachable controls [6].

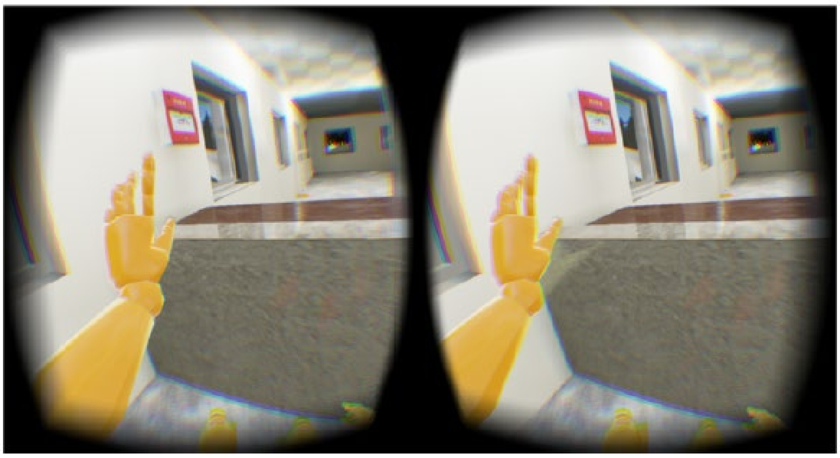

Figure 11-Simulated wheelchair inside a building [6]

Additionally, an exhaustive method for building a realistic virtual simulation of a fire in a learning environment has been put in place, with the goal of improving the VR experience by offering correct data for human and fire simulations. Virtual reality (VR) made it possible to combine human behavior and fire dynamic simulation in an interactive system, allowing the user to experience evacuation from every exit point, as seen on Figure 12 [7].

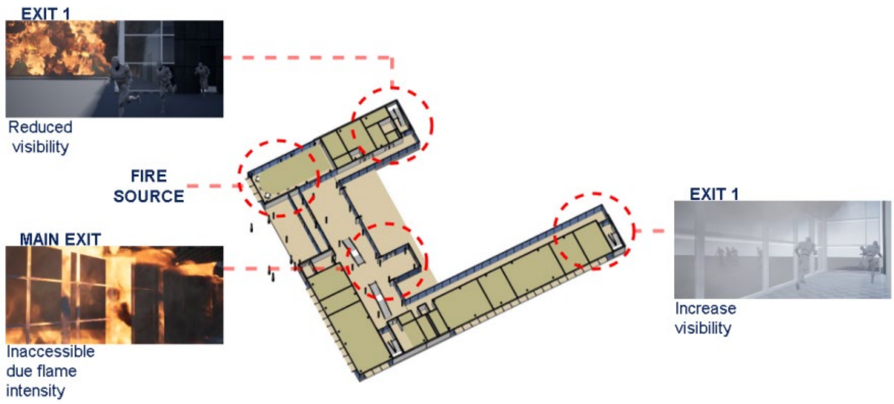

Figure 12-Fire simulation in a building showing the reducing visibility depending on the position of the user [7]

When taking into account the integration of human response components during the testing phase of buildings in an immersive environment like the one given by the CAVE setup, this aspect of VR becomes very pertinent [5].

Despite the promising applications, challenges persist. For instance, further work needs to be done on hand interaction and identification, as well as the integration of various sensor inputs for better posture detection, as certain problems were discovered while identifying the user's incorrect hand [6]. Additionally, fire behavior has an impact on the structure and building materials, which is something that the existing game technology does not take into account for detailed data-driven simulations of structural integrity or building materials. Overall, game engines can improve fire simulation [6][7].

However, the use of VR in the AEC industry has a lot of potential, notably for accessibility testing and evacuation planning. By basing simulations on data obtained from real-world events such as fire histories, drills, and laws, virtual reality and big data could enable more vivid design judgments for architects [7].

Modeling

VR has a potential in construction modeling. Construction modeling has always been a major phase during the project, as this step has been greatly improved the past years with the use of 3D tools and BIM.

In the Architecture, Engineering, and Construction (AEC) sector, VR adoption is rising, particularly in the context of Building Information Modeling (BIM) [11]. The ability of VR to provide immersive visualization of models (a feature that is unavailable in conventional 2D or 3D screens) is an essential component of VR [11]. Participants can now interact with the model in a more natural way and quickly adapt to the VR environment [11]. However, barriers like the expensive cost of appropriate gear and software, aversion to change, and a lack of familiarity with the technology are preventing VR from being adopted more widely within the AEC sector [11].

Figure 13-Design review with multiple project stakeholders using VR [11]

In contrast, VR has proven to have great potential for project planning and evaluation [13]. In a multi-user VR environment, project planners use VR to carry out a thorough sequencing and constructability study [13]. Better risk minimization, early detection of possible problems, and increased project execution efficiency are the results of these findings [13]. VR has further been utilized to pinpoint problem areas and draw attention to instances where the design wasn't the best from a production viewpoint [13]. If there are mistakes, users can modify or change the model, bringing construction knowledge into the design process [13]. This exposed a number of mistakes, highlighting the usefulness of VR as a tool for constructability evaluations [13].

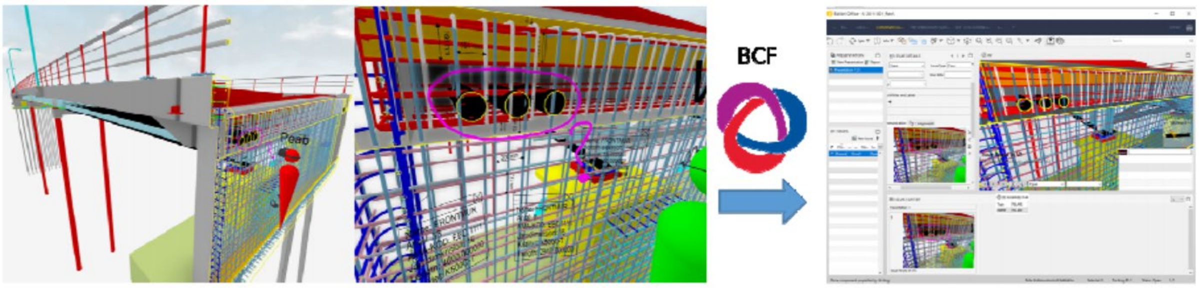

Figure 14-Interface allowing users to remotely report building issues (as proposed in [13])

On the other hand, an experiment demonstrates how VR can be used to improve maintenance accessibility in building design. The study participants were able to provide maintainability input using VR, with significantly higher time efficiency compared to traditional methods. VR also enabled quicker decision-making due to enhanced real-time spatial awareness [17].

Scenario	Experience group	Mean time required by group using VR (sec)	Mean time required by group with 10+ years' experience using VR (sec)	Mean Difference	P-Value
Scenario 1	1 to 5 years	57.33	69.7	-12.37	0.370629
	6 to 10 years	65.33	69.7	-4.37	0.937063
Scenario 2	1 to 5 years	60	47	13	0.272727
	6 to 10 years	39	47	-8	0.692308

Figure 15-Time needed for decision making as presented in [17]

In conclusion, VR has significant benefits for modeling and design in construction projects. It improves design evaluation, error discovery, and the exploration of alternative scenarios by offering immersive visualization and interactivity [11][13][17]. It can also speed up the design process by enabling real-time evaluation of changes [17]. However, barriers including high hardware and software costs and a lack of technology understanding prevent its wider implementation [11]. Therefore, efforts should be made in the future to enhance VR software, inform people about VR capabilities, and investigate the possible advantages of VR for the industry [11][17].

Researchers suggest integrating VR technology into the design phase to improve the maintainability of buildings [17]. By facilitating real-time problem-solving and quicker decision-making, VR can greatly enhance the efficiency of the design process. Furthermore, the researchers recommend conducting larger studies to understand better the potential of VR in the building industry. This could include exploring the impacts of changes to one piece of equipment on other interconnected systems. Such approach could further enhance the design process by allowing for a more comprehensive assessment of maintainability issues [17].

However, it is important to recognize the study's limitations. The study's small sample size might make it harder to generalize its results to the entire industry. Additionally, the interdependence of the hardware or applications in the mechanical room was not taken into account in the experimental design. Future research might need to take these links into account because modifications to one piece of hardware can have an impact on other systems. The study, taken as a whole, is a preliminary inquiry into how VR can facilitate more effective and inclusive design processes [17].

Construction planning

Analysis

Without a proper analysis, major issues can be encountered later in the project execution, leading to important changes in terms of architecture, or even planning. As such, this section addresses the contribution of VR to enhance construction analysis.

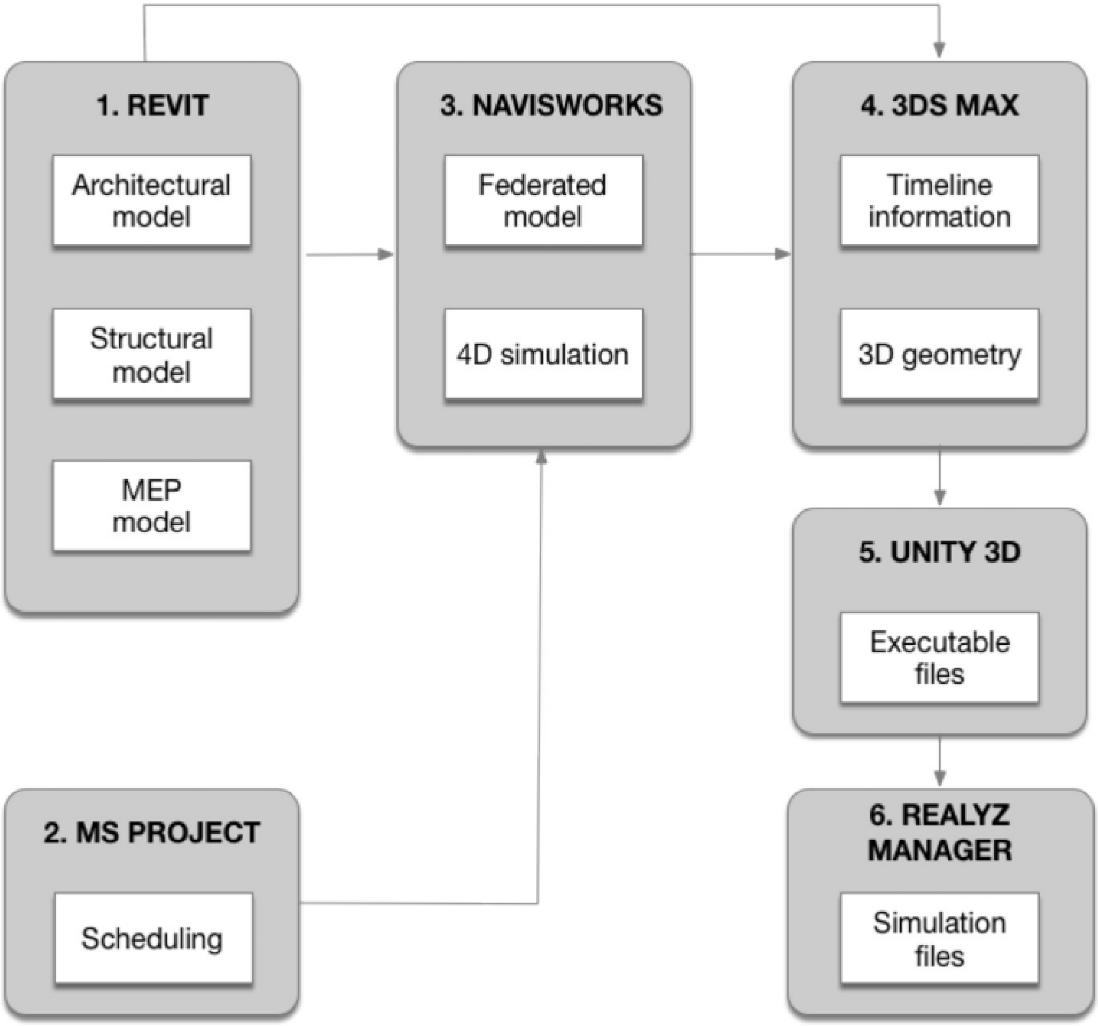

Figure 16-Exchanges between software used in [8]

It is evident from research done in Quebec, Canada [8], as well as another experimental investigation [9], that using VR in conjunction with 4D and Building Information Modeling (BIM) has benefits in the field of building planning. Both studies show that VR offers a collaborative environment akin to conventional coordination meetings, with higher performance and satisfaction ratings in most areas when compared to conventional approaches [8][9]. The implementation of VR has aided in project collaboration, training and education, safety management, and the discovery of spatiotemporal conflicts in terms of collaboration and visualization [9].

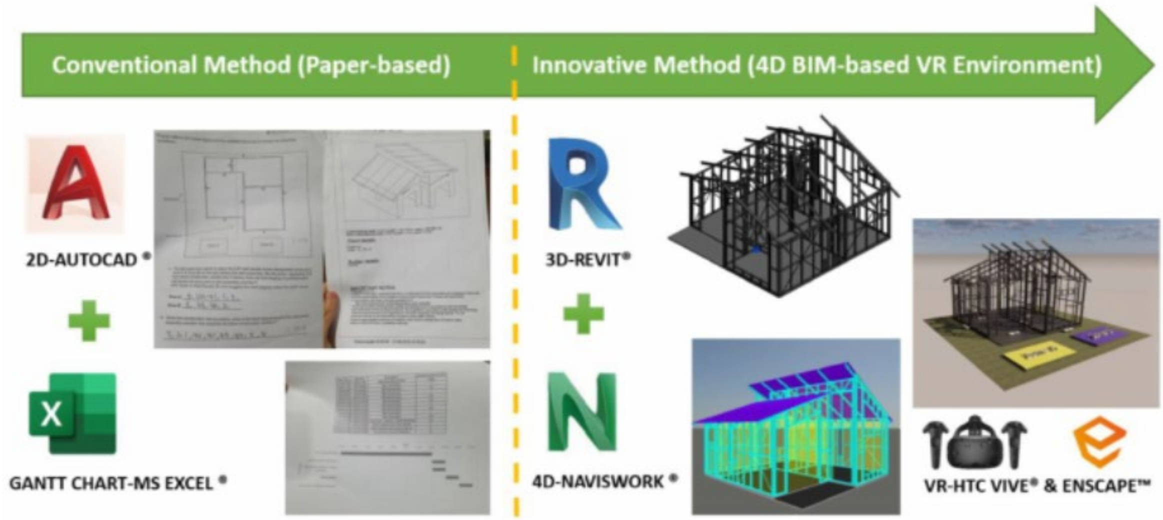

Figure 17-Comparison of traditional and implemented workflow [9]

Variable	Test type	Mean	S.D.	*t*-value	*p*-value
Spatial understanding	Paper-based	3.73	0.691	6.117	<0.001
	4D BIM-based VR	4.60	0.498		
Spatio-temporal conflicts	Paper-based	3.23	0.728	5.574	<0.001
	4D BIM-based VR	4.23	0.679		
Project collaboration between stakeholders	Paper-based	3.67	1.155	3.657	0.001
	4D BIM-based VR	4.57	0.568		
Training and education	Paper-based	3.00	1.363	3.953	0.001
	4D BIM-based VR	4.67	0.617		
Project schedule and sequencing	Paper-based	3.90	0.885	1.608	0.119
	4D BIM-based VR	4.20	0.484		
Safety management	Paper-based	3.32	1.189	4.475	<0.001
	4D BIM-based VR	4.20	0.484		
General	Paper-based	3.47	1.246	2.323	0.036
	4D BIM-based VR	4.20	0.561		

Table 4. Paired *t*-test on the questionnaire study based on the independent variables

Figure 18-Questionnaire results comparing the two workflows from the participants' point of view [9]

It is important to note that the combination of VR and 4D models revealed difficulties in some particular activities. As an illustration, both studies [8, 9] highlighted concerns in certain areas including the transmission of chronology information and the tally of visible structural parts. Interestingly, older methods proved to be more effective for some specialized jobs [8][9] despite the use of sophisticated technologies.

A third study [10] also highlighted the potential of VR and BIM to improve knowledge of costs and carbon footprint in the AEC industry. This study demonstrated how VR, BIM, and Life Cycle Assessment (LCA) together helped participants make more cost-effective and environmentally friendly decisions without sacrificing aesthetics [10].

Questions	Mean Overall	Mean N-CE	Mean CE	p-Value	Significant Difference
1. Do you use BIM for your work/projects?	2.52	1.58	3.63	0.000	Yes
2. Do you think cost estimation is essential in construction projects?	4.39	4.14	4.70	0.003	Yes
3. Do you think knowing the carbon footprint of a building is essential?	4.44	4.28	4.63	0.062	No
4. Have you used VR before?	2.44	2.25	2.67	0.255	No
5. To what extent, that you are aware of, is VR used in construction projects?	3.12	2.47	3.90	0.000	Yes
6. Do VR-models improve your perception of costs associated with different facades?	3.79	3.92	3.63	0.494	No
7. Do VR models improve your perception of the carbon footprint associated with different facades?	3.64	3.72	3.45	0.878	No
8. After knowing the experimental results, did the VR models affect your perception of costs and the carbon footprint of building façade systems?	4.44	4.67	4.17	0.028	Yes
9. Do you think using BIM + VR can help design efficient and sustainable buildings in the future, based on your current experience?	4.39	4.19	4.63	0.002	Yes
10. Do you envision a better tomorrow, where the goals of bringing downreducing global warming and making your country carbon neutral are attained?	4.89	4.83	4.97	0.643	No

Figure 19-Experiment questionnaire showing participants' feels (N-CE for non-civil engineers, CE for civil engineers) of VR use [10]

It is therefore evident that while VR provides significant advantages for construction planning, it is crucial to consider task-specific suitability when choosing between traditional and technologically advanced approaches. Furthermore, these research studies highlight the need for continued development and optimization of VR technologies to overcome existing challenges [8][9][10].

Three main conclusions may be drawn from these investigations. First, the combination of VR and BIM in parallel can considerably improve the effectiveness and accuracy of construction planning, resulting in a better understanding of the project as a whole and enhanced team communication. Second, even if using VR has numerous advantages, it's crucial to comprehend its limitations. Particularly, activities involving precise counting or time-based components may be better suited to conventional techniques. Third, by offering a clear picture of a project's cost and carbon footprint and influencing more sustainable design decisions, the usage of VR and BIM can result in more sustainable construction practices [10].

However, as these studies were relatively small-scale, further research is necessary to validate these findings on a larger scale and to continue to refine the VR-BIM-LCA framework [8][9][10]. Thus, while the current state of VR in construction planning is promising, it represents a field ripe for further research and innovation.

Planning

The innovative role of Virtual Reality (VR) in construction planning and project management has been the subject of multiple studies [16][18][19]. VR models provide a dynamic and interactive tool, addressing various challenges in the planning stages, from accurate visualizations to construction sequence simulations. Project planning of one of the key steps in any project, allowing for a better understanding and visualization of tasks, milestones, and subsequently improving decision-making and risk management. As such, multiple VR systems were implemented in studies.

A particular VR system offers a novel way to include worksite operations into the planning and scheduling of the entire construction project [16]. This technology does more than only assist in creating plans, map operations and facilities to their visual representations, and simulate work progress in a virtual setting. It includes dynamic site organization and keeps track of the arrival and withdrawal of resources in accordance with the schedule [16]. Notably, the system automates the integration of activities and facilities using a knowledge-based approach and permits high levels of user-system interaction [16].

Additionally, the network-based construction management software used by this VR system for scheduling allows users to input information about their projects [16]. It provides a thorough visual help for construction planning by combining the usefulness of Gantt bar charts for representing timelines and 3D models to visualize deviations from the plan [16]. The system was put through its tests on a number of simulated construction projects, demonstrating its capacity for emphasizing various site-related activities and equipment as well as the development of the construction over weeks [16].

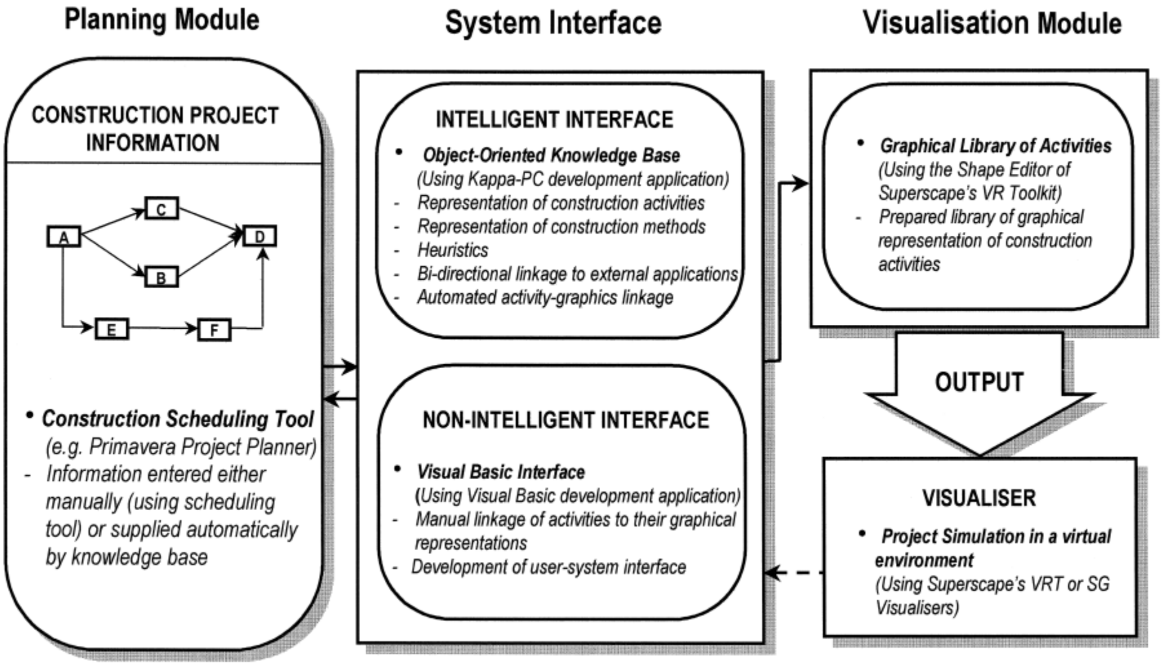

Fig. 5. Proposed system components and operation.

Figure 20-Proposed system components and operation [16]

A study that highlighted yet another use case for VR focused on teaching students how to comprehend the many steps required in building a wall using a VR model [18]. The external brick wall in the case study served as a model for the construction process' actual challenges [18]. A construction plan can be followed by manipulating individual wall components thanks to the integration of the VR model into the EON system [18]. To better understand the specifics of each part and stage, the user can interact with the virtual construction process from any aspect [18]. Virtual reality (VR) in education offers a dynamic learning tool that may be used in regular classrooms or online learning environments [18].

Another example is a VR-based application that uses a 4D (3D+time) model for building planning and was developed as part of a research project at the Technical University of Lisbon [19]. The application displays designs in 3D and incorporates them with construction schedules to show construction projects graphically and interactively throughout time [19] (Figure 21). The authors suggested that this VR tool can more readily identify errors before building begins, resulting in time and cost savings [19]. The VR model is claimed to be more intuitive than other 4D models due to the incorporation of updated photographs obtained from the construction site, despite the time-consuming nature of preparation for interaction with the application [19].

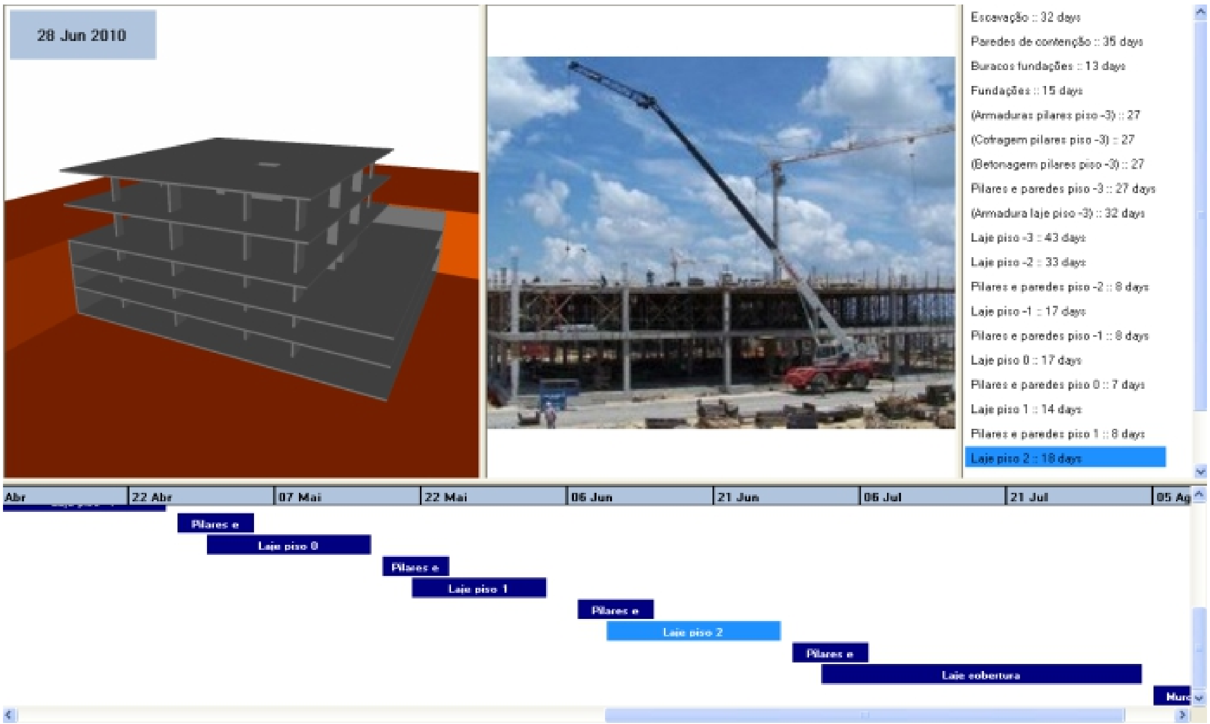

Figure 21-User interface showing the different modules of visualization [19]

Through their sophisticated graphic and interactive features, these VR models have the potential to speed up maintenance planning [19]. The maintenance model helps define appropriate rehabilitation plans, while the VR construction model adds to error-free construction with no unnecessary postponements [19].

In summary, VR represents a substantial breakthrough in building planning, moving beyond visual simulation to add a high level of intelligence and engagement to the whole process [16][18][19]. The use of VR aids in error detection, cuts down on time and expense, and allows for an accurate representation of the building process. When it comes to project development and decision-making in the field of construction and maintenance, its interaction and networking capabilities offer significant advantages [19]. The potential for better planning, training, and maintenance techniques grows along with VR technology as it develops and is integrated into the construction sector.

Conclusion

During this state of the art, we were able to see and better understand the potential of a technology such as VR in terms of improving the preliminary phases of a construction project, while making a point of honor on collaboration.

With the methodology chosen for the realization of this state of the art, we were able to fix 3 aspects where the implementation of VR is interesting, namely collaboration, design, and construction planning. These 3 points allowed us to show the advantages of this technology, whether in the better understanding of the project, the communication between project members with different theoretical or practical knowledge.

The integration of VR also offers advantages in conception, where design stakeholders can collaboratively manipulate and interact with virtual models, allowing better analysis and simulation of potential accessibility flaws, cost assessment, or emergency scenarios.

In conclusion, VR is already being used in other industries, and with the emergence of new implementations like the Metaverse, it's a technology to watch. Although current configurations can be expensive, a democratization of this technology would make it easier to access for any type of infrastructure in the future.

References

[1] A. Abbas, M. Choi, J. B. Seo, S. H. Hyun and H. Li, "Effectiveness of Immersive Virtual Reality-based Communication for Construction Projects," *Ksce Journal of Civil Engineering,* vol. 23, pp. 4972–4983, November 2019, doi: 10.1007/s12205-019-0898-0.

[2] B. A. Asl and C. S. Dossick, "Immersive VR versus BIM for AEC Team Collaboration in Remote 3D Coordination Processes," *Buildings,* vol. 12, p. 1548, September 2022, doi: 10.3390/buildings12101548.

[3] M. S. U. Rehman, N. Abouelkhier and M. T. Shafiq, "Exploring the Effectiveness of Immersive Virtual Reality for Project Scheduling in Construction Education," *Buildings,* vol. 13, p. 1123, April 2023, doi: 10.3390/buildings13051123.

[4] O. Christ, A. Papageorgiou, P. Meier, A. Urech, A. Boroch, M. Huang and C. Eichhorn, "Immersive virtual spacewalking in stakeholder workshops:the effect of immersive, BIM-driven design and interaction tools on human sense of presence," 2022, doi: 10.54941/ahfe1002743.

[5] T. Lin, "VIRTUAL REALITY OF EARTHQUAKE GROUND MOTIONS FOR EMERGENCY RESPONSE," 2017, doi: 10.7712/120117.5551.18465.

[6] T. Hilfert and M. König, "Low-cost virtual reality environment for engineering and construction," *Visualization in Engineering,* vol. 4, January 2016, doi: 10.1186/s40327-015-0031-5.

[7] H. Park, D. Panya, H. Goo, T. Kim and J. H. Seo, "BIM-based Virtual Reality and Human Behavior Simulation For Safety Design," 2018.

[8] C. Boton, "Supporting constructability analysis meetings with Immersive Virtual Reality-based collaborative BIM 4D simulation," *Automation in Construction,* vol. 96, p. 1–15, December 2018, doi: 10.1016/j.autcon.2018.08.020.

[9] A. Rashidi, W. Y. Yong, D. Maxwell and Y. Fang, "Construction planning through 4D BIM-based virtual reality for light steel framing building projects," *Smart and Sustainable Built Environment,*October 2022, doi: 10.1108/sasbe-06-2022-0127.

[10] A. Kamari, A. Paari and H. Ø. Torvund, "BIM-Enabled Virtual Reality (VR) for Sustainability Life Cycle and Cost Assessment," *Sustainability,* vol. 13, p. 249, December 2020, doi: 10.3390/su13010249.

[11] R. Zaker and E. Coloma, "Virtual reality-integrated workflow in BIM-enabled projects collaboration and design review: a case study," *Visualization in Engineering,* vol. 6, September 2018, doi: 10.1186/s40327-018-0065-6.

[12] J. Du, Y. Shi, Z. Zou and D. Zhao, "CoVR: Cloud-Based Multiuser Virtual Reality Headset System for Project Communication of Remote Users," *Journal of the Construction Division and Management,* vol. 144, February 2018, doi: 10.1061/(asce)co.1943-7862.0001426.

[13] M. Johansson and M. Roupé, "VR in Construction – Multi-User and Multi-Purpose," *Proceedings of the 22nd International Conference on Construction Applications of Virtual Reality (CONVR 2022),* vol. 22, p. 248–259, 2022.

[14] J. Du, Z. Zou, Y. Shi and D. Zhao, "Zero latency: Real-time synchronization of BIM data in virtual reality for collaborative decision-making," *Automation in Construction,* vol. 85, p. 51–64, January 2018, doi: 10.1016/j.autcon.2017.10.009.

[15] S. Bourlon and C. Boton, Automating the Integration of 4D Models in Game Engines for a Virtual Reality-Based Construction Simulation, 2019, pp. 123–132. doi: 10.1007/978-3-030-30949-7_14.

[16] A. Retik and A. Shapira, "VR-based planning of construction site activities," *Automation in Construction,* vol. 8, pp. 671–680, August 1999, doi: 10.1016/s0926-5805(98)00113-7.

[17] D. Bhonde, P. A. Zadeh and S. Staub-French, "Evaluating the use of virtual reality for maintainability-focused design reviews," *Journal of Information Technology in Construction,* vol. 27, p. 253–272, March 2022, doi: 10.36680/j.itcon.2022.013.

[18] A. Z. Sampaio and P. Henriques, "Interactive project planning in construction based on virtual reality technology," 2003.

[19] A. Z. Sampaio, J. C. Prata, A. M. P. Gomes and D. P. Rosário, Construction and Maintenance Planning Supported on Virtual Environments, 2012, doi: 10.5772/46409.

[20] "BIM Benefits | Why Use BIM? | Autodesk," [Online]. Available: https://www.autodesk.com/industry/aec/bim/benefits-of-bim.

[21] "BIMXplorer," [Online]. Available: https://www.bimxplorer.com/.

[22] W. contributors, "Building information modeling," June 2023. [Online]. Available: https://en.wikipedia.org/wiki/Building_information_modeling.

[23] M. Tobias, "What Does MEP Mean in Construction?," June 2023. [Online]. Available: https://www.ny-engineers.com/blog/what-does-mep-mean-in-construction.

[24] P. Architecture, "Editor's Pick: 10 best Building Information Modeling (BIM) tools and workflows," April 2023. [Online]. Available: https://parametric-architecture.com/10-best-building-information-modeling-bim-tools-and-workflows/.

[25] "Industry Foundation Classes (IFC) - buildingSMART International," June 2019. [Online]. Available: https:// technical.buildingsmart.org/standards/ifc.

[26] "UniFormat® - Construction Specifications Institute," [Online]. Available: https://www.csiresources.org/standards/uniformat.

[27] R. Sheldon, "virtual reality," August 2022. [Online]. Available: https://www.techtarget.com/whatis/definition/virtual-reality.

[28] W. contributors, "Virtual reality," October 2001. [Online]. Available: https://en.wikipedia.org/wiki/Virtual_reality.