MSc Program
Engineering Management

Investing the use of virtual reality in the design and planning phase of construction projects

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Em.O.Univ.Prof. Dr.h.c.mult. Dipl.-Ing. Dr.techn. Peter Kopacek

Shirin Mohammadi, MSc

12130523

Vienna, 15.03.2023

ACADEMY FOR CONTINUING EDUCATION

Affidavit

I, **SHIRIN MOHAMMADI, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "INVESTING THE USE OF VIRTUAL REALITY IN THE DESIGN AND PLANNING PHASE OF CONSTRUCTION PROJECTS", 61 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 15.03.2023

____
Signature

Abstract

Virtual reality technology has emerged as a potential solution for the challenges faced by the construction industry in the design and planning phase of construction projects. Traditional methods, such as 2D drawings and physical models, are often inadequate in conveying the complexity and intricacies of a building, making it difficult for stakeholders to collaborate effectively. Virtual reality technology can help address these challenges by providing a more immersive and interactive design and planning experience, allowing stakeholders to visualize and experience a building before it is constructed. In addition, virtual reality technology can also be used to simulate construction processes and identify potential safety hazards. However, there is still a lack of understanding regarding the effectiveness of virtual reality technology in the construction industry. This thesis aims to investigate the current state of virtual reality technology in construction, exploring its potential benefits and challenges in the design and planning phase of construction projects through a literature review and case studies of projects that have used virtual reality technology.

Keywords: virtual reality, construction industry, design, planning, visualization, case studies.

Table of Contents

1. INTRODUCTION

The concept of virtual reality can be traced back to the early days of practical photography in the 1800s. The first stereoscope, using twin mirrors to project a single image, was invented in 1838 and evolved into the View-Master, which was patented in 1939 and is still in production today. The term "virtual reality" was first used in the mid-1980s by Jaron Lanier, founder of VPL Research, who developed the necessary gear, including goggles and gloves, to experience this technology. However, prior to this, simulated environments were being developed, with Morton Heilig's Sensorama in 1956 being a significant milestone. The 1970s and 1980s saw significant progress in optical and haptic devices that allowed people to move around in virtual space. Today's virtual reality gear owes a great deal to the pioneering inventors of the past six decades, who paved the way for accessible, high-quality, and low-cost devices. (History of virtual reality, n.d.)

The construction industry is one of the largest and most complex industries in the world, and its success depends on effective collaboration and communication among stakeholders. The design and planning phase of construction projects is critical to the success of a project, as it sets the foundation for the entire construction process. Traditionally, this phase has relied on 2D drawings, physical models, and blueprints to communicate design intent. However, these methods are often inadequate in conveying the complexity and intricacies of a building.

Virtual reality (VR) technology has emerged as a potential solution to these challenges by providing a more immersive and interactive design and planning experience. VR technology allows stakeholders to visualize and experience a building before it is constructed, which can help identify potential issues and improve collaboration among stakeholders. Furthermore, VR technology can also be used to simulate construction processes and identify potential safety hazards.

Despite the potential benefits of VR technology, there is still a lack of understanding of its effectiveness in the construction industry. Therefore, this thesis aims to investigate the current state of VR technology in the construction industry and explore its potential benefits and challenges in the design and planning phase of construction projects. The research will include a literature review of existing studies on the use of VR technology in construction, as well as case studies of construction projects that have used VR technology in the design and planning phase.

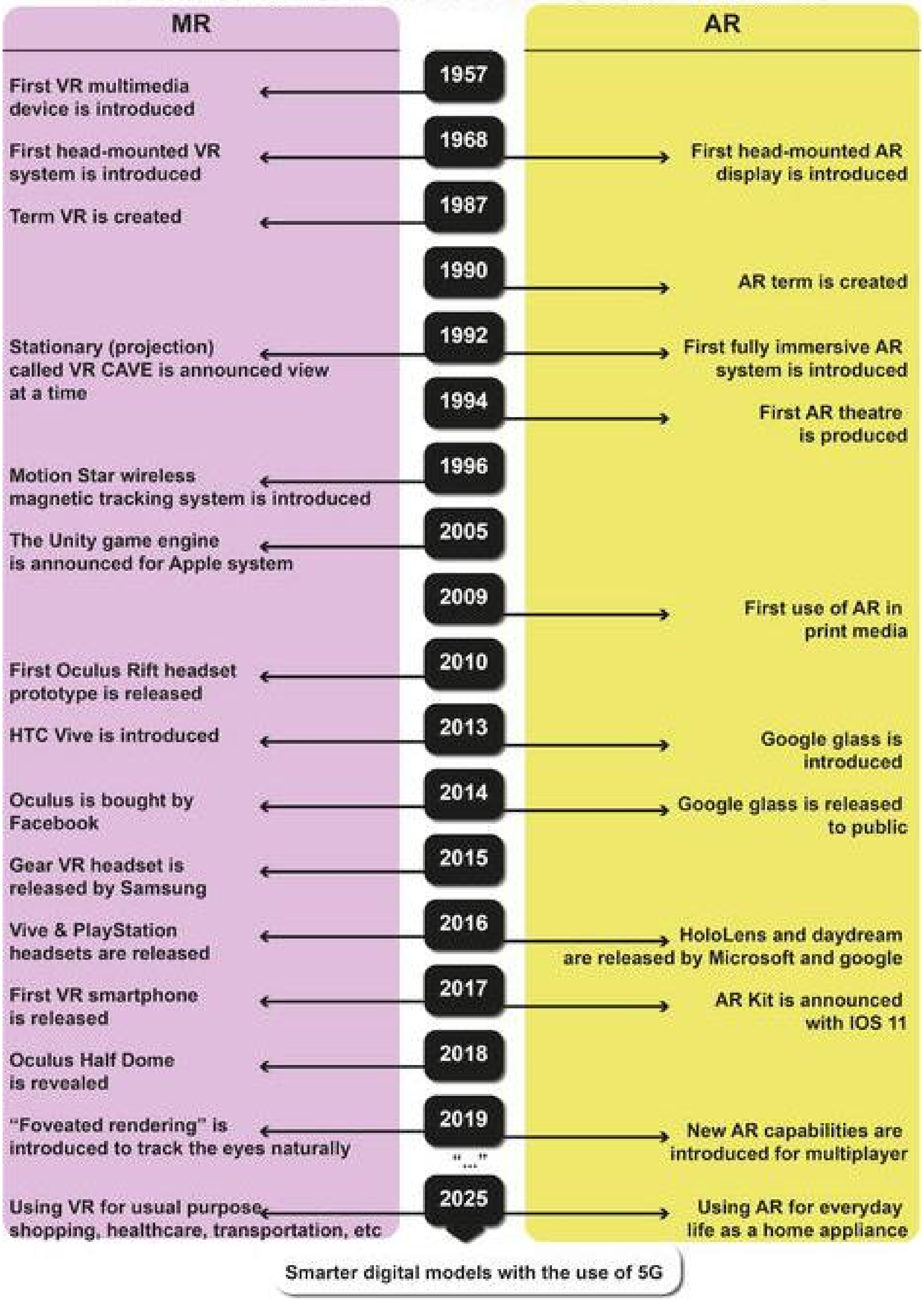

Fig. 1: Timeline of Virtual Reality and Augmented Reality technologies and the predictable future of them (Ghobadi & Sepasgozar, 2020)

2. LITERATURE REVIEW

2.1 Virtual reality technology in construction

The construction industry is one of the most significant sectors in terms of the global economy, contributing significantly to gross domestic product (GDP) and employment. However, it is also one of the most challenging industries due to its complex nature and a wide range of stakeholders involved in the construction process. The construction industry involves various activities, including design, planning, material selection, construction, maintenance, and operation. These activities are often performed in challenging environments, including remote and hazardous locations, making it difficult to manage and control the construction process. Additionally, the construction industry has been criticized for its inefficiencies, cost overruns, delays, and safety issues. To overcome these challenges, the construction industry has been seeking innovative solutions, including the adoption of emerging technologies such as virtual reality (VR).

2.2 Levels of Virtual Reality

Virtual reality can be defined by the degree of immersion or realism it provides. There are generally four levels of virtual reality:

- Non-immersive VR: Non-immersive VR refers to virtual reality experiences that are not fully immersive. This includes experiences that use a computer screen or projection to create a virtual environment. Non-immersive VR can be useful for visualizing 3D models or for basic training and simulation exercises.
- Semi-immersive VR: Semi-immersive VR refers to virtual reality experiences that are partially immersive. This includes experiences that use a larger screen or multiple screens to create a more immersive environment. Semi-immersive VR can be useful for training and simulation exercises that require more realism and interaction.
- Fully immersive VR: Fully immersive VR refers to virtual reality experiences that are fully immersive, providing a complete sense of presence in a virtual environment. This includes experiences that use head-mounted displays (HMDs) to fully immerse the user in the virtual environment. Fully immersive VR can be used for training, simulation, and gaming applications.
- Haptic VR: Haptic VR refers to virtual reality experiences that provide not only visual and auditory feedback but also tactile feedback, simulating touch and force feedback. This includes experiences that use haptic gloves, suits or chairs to create a more realistic experience. Haptic VR can be used for medical simulations, training for hazardous environments, or even for remote surgery.

Overall, the level of immersion in VR technology can impact the user experience and the potential applications for training, simulation, and other fields.

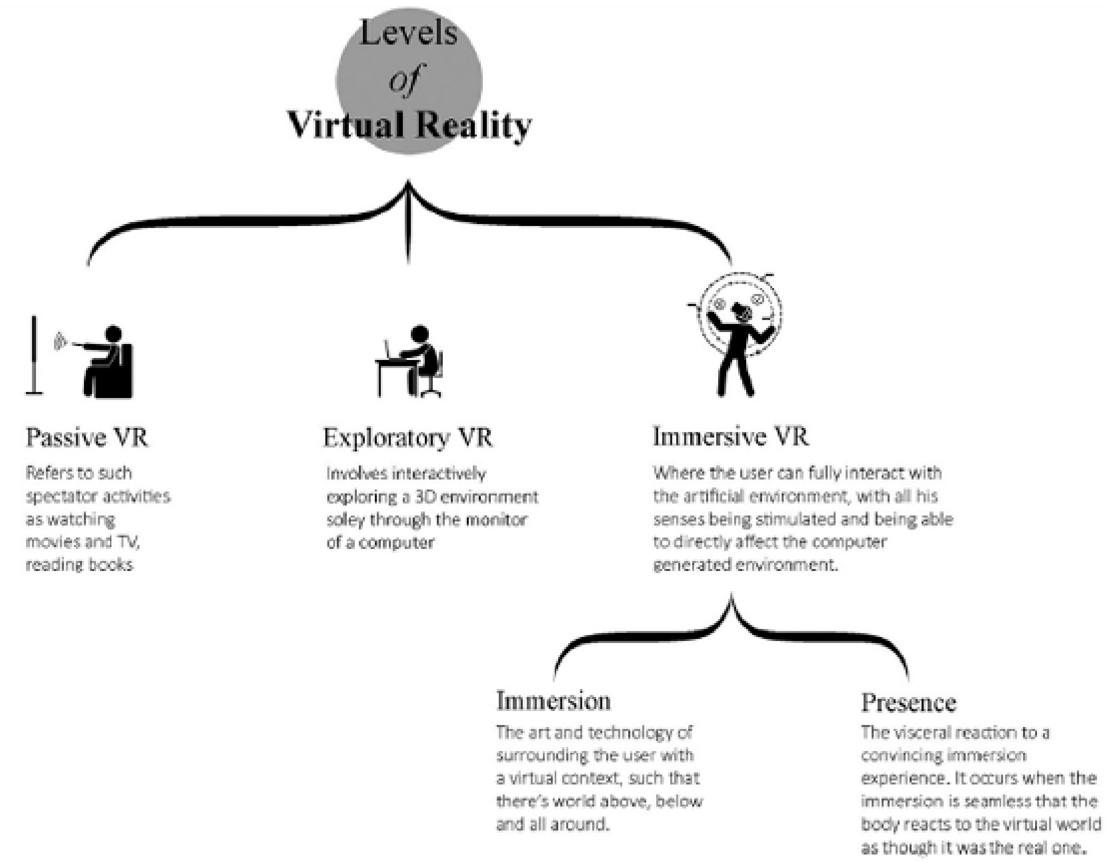

Fig. 2: Levels of virtual reality

2.3 Current State of Virtual Reality Technology in Construction

2.3.1 Design Collaboration

Designers collaborate with colleagues and stakeholders throughout the design process, relying on feedback to adapt designs. Traditional design reviews are typically done in person using 2D screens, physical models, and other similar tools. However, these reviews can be costly and challenging, especially for those who are not design professionals or who have difficulty visualizing technical illustrations. Virtual reality solutions can greatly improve the efficiency and impact of design reviews. By moving the design review process to an immersive virtual environment, time savings can be over 90% compared to traditional processes. Professional VR headsets now have the visual quality and colour reproduction needed to build and show lifelike digital reproductions of actual products, and changes can be made instantly and reflected in the digital model for all review participants to see. This flexibility benefits global teams, enabling them to collaborate earlier in the process and removing the need for travel to meet colleagues in other locations, ultimately saving time and money. (A guide for virtual and Mixed Reality for Industrial Design)

Kia Europe's automotive design process previously relied on 2D screen reviews and physical models to refine and develop surfaces. However, designers are now using Varjo's VR and XR headsets to complement their workflow, making their visualization work more effective and showcasing projects in new ways. For example, designers can review a virtual model directly against a physical model in the same room or augment an existing clay model with virtual details. This use of virtual and mixed reality solutions can provide designers with a more immersive and efficient design process, ultimately resulting in better products. (Case Kia: Global design reviews can go from days to an hourr , n.d.)

Fig. 3: Kia's European design studio, led by Gregory Guillaume, is a pioneer in integrating new technologies into their design workflow. With a digital 3D department, design teams and visualization experts, its goal is to always exceed expectations – both for Kia customers and the company's leadership in South Korea.

Using VR gives decision-makers a 1:1 scale experience of the project and proposed solution. The implementation of virtual reality (VR) technology in the building design process enhances the satisfaction of building owners and end-users by providing them with the ability to follow the process more closely and frequently, with clear communication of proposed solutions that require no prior knowledge of Building Information Modelling (BIM) or floor plans. This approach ensures that accessibility is not an afterthought by involving advisors and test groups, such as wheelchair users, in the design review process. Compliance with accessibility regulations alone does not necessarily lead to the most practical solution. Furthermore, VR can also be used in the healthcare industry to facilitate the review of treatment and operation rooms by doctors and nurses, allowing for the evaluation of functional size and equipment layouts, as well as acceptable sightlines from the outside. Additionally, life safety engineers and construction safety managers can utilize VR technology to review a virtual building, allowing for the planning of scaffolding, tie-offs, and access to ensure proper safety measures.

2.3.2 Global shipments of VR devices

In 2022, global shipments of VR/AR devices declined by more than 12% compared to the previous year, with a total of 9.6 million devices shipped, according to CCS Insight. Similarly, NPD Group reported a 2% year-over-year decline in US annual sales of VR headsets, totalling $1.1 billion as of early December. Despite these declines, businesses and consumers continue to take advantage of a strong product portfolio of VR headsets, AR smart glasses, and advanced enhanced AR headsets. However, the economic uncertainties have dampened the outlook for virtual and augmented reality (VAR) technology adoption in the US.

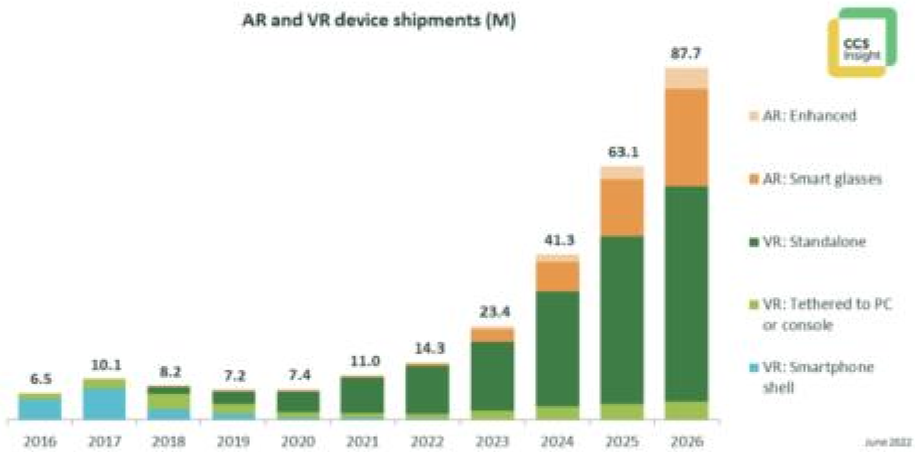

Fig. 4: Global shipments of VR/AR devices (Virtual and Augmented Reality ,Finding real opportunities in virtual worlds, n.d.)

2.4 Virtual Reality for Design and Construction Education

Virtual reality can be utilized in various aspects of design and construction education, including training for construction site safety, familiarization with construction processes and equipment, design review and simulation, and communication and collaboration among project stakeholders. By using virtual reality technology, students can gain hands-on experience in various aspects of design and construction in a safe and controlled environment. This can lead to improved knowledge retention and better performance when working on real-world projects.

The instructor collected feedback from students about the benefits of using VR headsets. Figure 2 shows the student scores on eight characteristics, including learnability, interoperability, visualization, real-world similarity, interaction, creativity, motivation, and comfort. Students found VR to be a motivator for learning design and construction concepts, allowing for greater interactivity than traditional lectures. Although comfortable using VR, some students experienced motion sickness and had to master several software applications to handle interoperability issues. However, students considered VR ideal for visualizing design and construction environments. (Alizadehsalehi, Hadavi, & Huang, 2019)

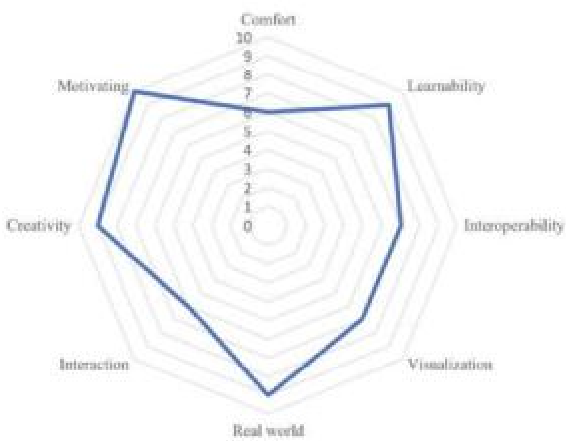

Fig. 5: The opinions provided by participating students.

3. METHODOLOGY

3.1 Data collection methods

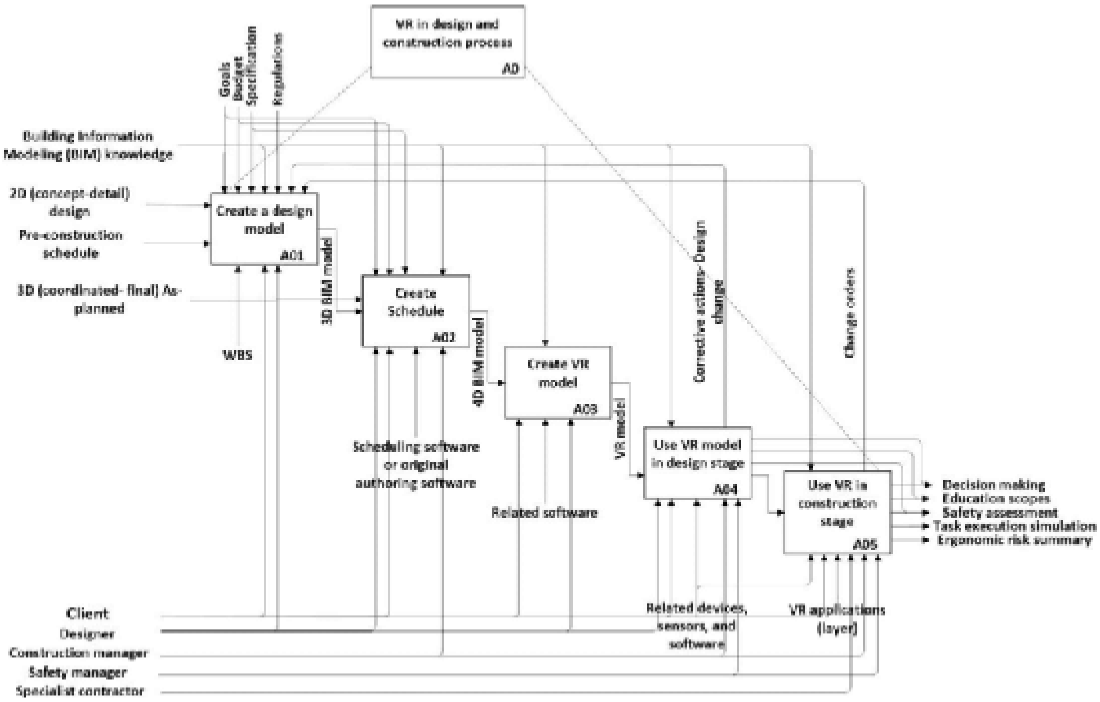

Fig. 6: Model for Using VR in Design and Construction

Figure 3 depicts the various stages involved in creating a model for VR use during construction, starting with gathering data such as architectural, structural, and MEP design data, preconstruction schedules, cost estimates, and other essential information. These data are integrated to create a federated 4D BIM-based Digital as-planned model (A01) and (A02), from which a VR model is derived based on specifications, BIM knowledge, and input from designers and stakeholders (A03). The VR model is then used to analyze the design, evaluate alternative decisions, and make necessary corrections (A04). Once approved by relevant stakeholders, the design is transferred to construction site stakeholders for implementation (A05). (Alizadehsalehi, Hadavi, & Huang, 2019)

3.1.1 VR methods during design and construction of new buildings

To create a VR experience for a building project, the process typically involves three stages, as depicted in Figure 1. Firstly, CAD drawings are simplified to schematic references using software such as AutoCAD. In the second stage, the model is imported into a 3D modelling program, such as Archicad, Rhinoceros, Revit, 3ds Max, or Sketchup, and the architectural information is extruded to create a 3D model with textures. The third stage involves importing the model into VR software, defining location coordinates, and optimizing the visual features for an immersive user experience. This may include lighting configuration, assigning specific properties to textures, and defining animations and information windows. Software such as Unreal Engine and Unity are commonly used to develop sophisticated VR experiences.

The selection of software families is a critical step in the development process to ensure compatibility and efficiency while avoiding any loss of information. Figure 1 presents the most widely used software at each stage of the process and how they are connected according to software system (packages) compatibility. (Orihuela, Pacheco, Orihuela, Yaya, & Aguilar, 2019)

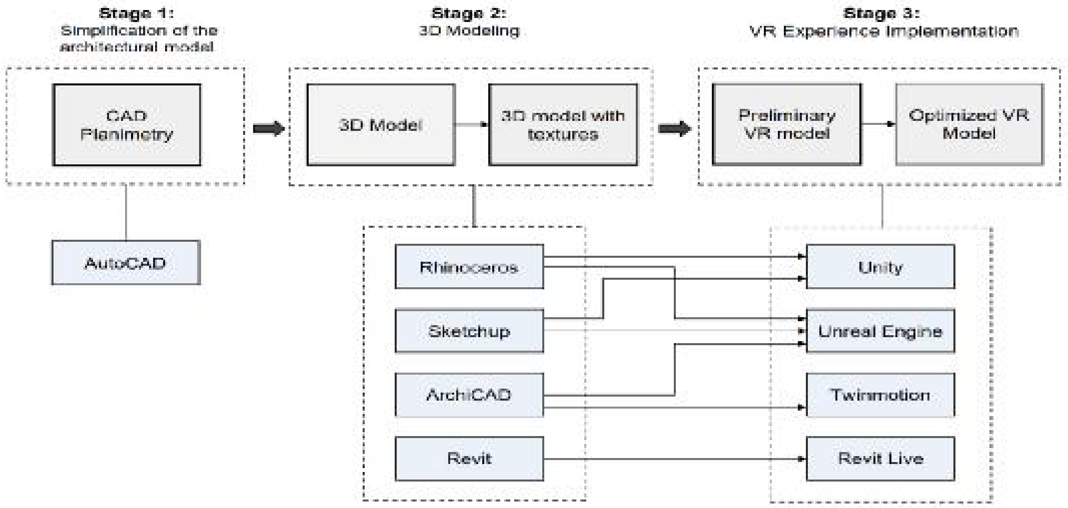

Fig. 7: A broad overview of the process for implementing a building project with the use of VR.

3.1.2 VR in Safety training: Integrating Simulation Technology into Space Design Teaching

One approach is to use the case teaching method, which allows students to experience the environment and incorporate their current knowledge into typical cases. This teaching method can make full use of multimedia technology and computer information resources to create a vivid and creative classroom teaching scenario that enables students to take full advantage of their own knowledge and deepen their understanding of knowledge in realistic teaching situations. The case teaching method can express complex theories in simple terms through practical engineering examples or real-life examples, which can effectively improve students' ability to analyze problems and stimulate their enthusiasm.

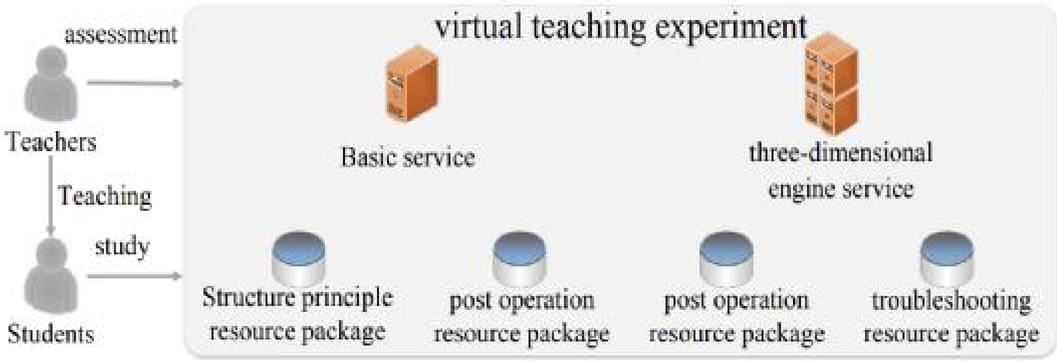

Fig. 8: the relationship between simulation resource packets and the overall virtual experiment teaching model

Another method is to integrate simulation resource packet technology based on Virtools into space design teaching. This technology can determine the simulation resource packet suitable for the whole teaching process according to the specific content and training way of different professions. The simulation resource packet technology includes four simulation resource packet modules, namely, structure principle simulation resource packet, post operation simulation resource packet, maintenance simulation resource packet, and troubleshooting simulation resource packet. The structure principle simulation resource packet is the most important experiment frame of the entire virtual experiment teaching, and its major function is to enable the clear three-dimensional virtual presentation of the entire virtual experiment teaching. The post operation simulation resource packet is developed based on the corresponding structural standards and resources environment provided by the entire structure principle simulation resource packet to meet the use requirements of the entire virtual experiment teaching model. The maintenance simulation resource packet offers the underlying maintenance feature for the entire virtual experiment operation system, and the troubleshooting simulation resource packet plays a complementary role.

The last method is integrating simulation virtual technology into the space design teaching model. The virtual experiment teaching model is mainly used in the teaching of “space design,” an architecture course. The main research object of such courses is the interior space after decoration. The virtual experiment teaching model can determine the appropriate virtual experiment operation environment and realize the placement of specific mobile decorations in the simulated three-dimensional virtual building space through the three-dimensional virtual experiment operation. The overall framework of the virtual experiment teaching model includes the corresponding information learning module, the feedback module for exchanges between students and the experiment evaluation module. By integrating simulation virtual technology into space design teaching, students can enhance their understanding and practical skills in space design. (Wu, 2018)

3.1.3 An Overview of Virtual Reality Tools

Virtual reality technology is revolutionizing the way construction projects are planned, designed, and executed. By using virtual reality hardware and software, construction professionals can create immersive 3D environments that allow them to visualize and interact with building designs in real time. However, with so many different types of virtual reality hardware and software available, it can be challenging to determine which tools are best suited for a particular project.

- Virtual Reality Headsets:

Virtual reality (VR) headsets are an essential component of the VR experience, as they are responsible for creating the immersive environment that users can explore. A VR headset typically consists of a display screen, lenses, and motion sensors, which allow users to see and interact with the virtual environment. The display screen is usually split into two separate images, one for each eye, which creates the 3D effect that makes the experience feel more realistic. The motion sensors track the user's head movements, which is then translated into movement within the virtual environment, allowing the user to look around and interact with objects.

There are currently several types of VR headsets available on the market, each with its own set of advantages and disadvantages. The most well-known VR headset is the Oculus Rift. The Rift features high-resolution displays, integrated headphones, and motion controllers, which provide a more immersive experience for users. (Oculus Quest, 2022)

Another popular VR headset is the HTC Vive (HTC Vive, 2022). The Vive features room-scale tracking, which allows users to move around within the virtual environment and includes motion controllers that provide a more natural way of interacting with objects. The Vive also features a front-facing camera, which allows users to see the real world without having to take off the headset.

Atom is an innovative engineering-grade augmented reality system that combines a construction safety headset, AR displays, and in-built computing power to deliver precise on-site construction solutions. This powerful custom-built engineering tool enables construction teams to view and position holograms of 3D design models with millimeter accuracy on the construction site. The Atom AR system is the world's most accurate AR system that enhances the safety, productivity, and accuracy of construction operations. Its sophisticated features make it an indispensable tool for construction teams looking to streamline their operations and deliver outstanding results. The Atom not only provides powerful engineering-grade AR capabilities but also offers tools to manage data and enhance collaboration. With the Manage feature, construction teams can maximize site-wide transparency by managing issues, assigning tasks, updating workflows, and sharing pictures and videos with the team. The Immersive AR Model Control feature allows users to target specific layers of the model, select elements for inspection, and scale down and crop models for a new perspective. The Atom also enables remote access to augmented reality, allowing for real-time collaboration and decision-making from anywhere. Additionally, the Atom is built to work offline, so even without an internet connection, users can continue to work and sync data as soon as a connection is restored.

Fig. 9: The Atom, XYZ Reality's Engineering Grade AR headset (Augmented Reality for Construction., 2023)

In recent years, standalone VR headsets have also become increasingly popular. These headsets, such as the Oculus Quest and the Lenovo Mirage Solo, do not require a separate computer or console to operate, making them more accessible and portable. Standalone headsets typically have lower specifications than their PC counterparts, but still offer a good VR experience.

Despite the many benefits of VR headsets, there are still some limitations that need to be addressed. One of the main issues is the motion sickness that some users experience when using VR headsets, which can be caused by the discrepancy between the movement that users perceive in the virtual environment and the lack of corresponding movement in the real world.

- Virtual Reality Gloves and Controllers:

Virtual reality (VR) technology has been increasingly used in the construction industry to improve collaboration, reduce errors, and enhance safety. The use of VR gloves and controllers can further enhance the user's experience and interaction with the virtual environment.

VR gloves allow users to have a more immersive experience by providing haptic feedback, allowing them to touch and manipulate objects within the virtual environment. This is especially useful in the construction industry as it allows stakeholders to interact with 3D models of buildings and infrastructure, providing a more realistic understanding of how the final product will look and function. VR gloves can also be used for training purposes, allowing workers to practice specific tasks and identify potential safety hazards in a controlled environment.

VR controllers are another tool that can be used to improve the user's experience in a VR environment. They allow users to navigate through the virtual environment and interact with objects using natural hand movements, providing a more intuitive and seamless experience. In the construction industry, VR controllers can be used to simulate construction processes, allowing stakeholders to visualize the construction sequence and identify potential issues before construction begins.

While the use of VR gloves and controllers in the construction industry is still in its early stages, it has the potential to revolutionize the way construction projects are designed and executed. However, there are still challenges to be addressed, such as the cost and accessibility of the technology, as well as the need for proper training and education for users.

In conclusion, VR gloves and controllers can significantly enhance the user's experience and interaction with the virtual environment, providing a more realistic and immersive experience. In the construction industry, this technology can improve collaboration, reduce errors, and enhance safety, ultimately leading to more efficient and successful construction projects.

- Virtual Reality Software:

Virtual Reality (VR) technology is revolutionizing the way construction professionals visualize and plan building projects. By using VR software, construction users can create immersive experiences that simulate real-world environments and allow them to make informed decisions about design, construction, and maintenance.

One of the most important benefits of using VR software in construction is that it helps to reduce errors and increase efficiency. With VR, users can create 3D models of buildings and simulate various scenarios, such as equipment placement, structural integrity, and interior design. This allows them to identify potential issues early on and make necessary changes before construction begins, saving time and money in the long run.

Another benefit of VR software for construction users is improved communication and collaboration. VR enables users to share their designs and ideas in a more engaging and intuitive way, making it easier for stakeholders to understand and provide feedback. By using VR, designers, engineers, and architects can work together more effectively, resulting in better project outcomes.

There are several VR software options available for construction users, such as Unity, Revit, and SketchUp. Unity is a popular choice for creating immersive experiences and has a wide range of features that make it suitable for creating complex simulations. Revit is a Building Information Modeling (BIM) software that enables users to create 3D models of buildings and analyze various design scenarios. SketchUp is a user-friendly 3D modeling software that is ideal for creating basic designs and visualizations.

Overall, VR software is an innovative and powerful tool that is transforming the construction industry. By using VR, construction users can create more accurate and detailed designs, reduce errors, and improve collaboration, resulting in better project outcomes and increased client satisfaction.

- Virtual Reality Accessories:

Virtual Reality (VR) technology has come a long way in recent years, and with that has come a range of VR accessories that enhance the overall experience. These accessories can be used with VR headsets to provide a more immersive experience and make it easier to interact with virtual environments.

One of the most common VR accessories is the handheld controller. These controllers are designed to be used with VR headsets and allow users to interact with virtual objects in the environment. They typically feature buttons, triggers, and joysticks that can be used to manipulate objects and navigate menus. Some controllers also have motion sensors, which allow for more natural movements and gestures.

Another popular VR accessory is the VR treadmill. These treadmills are designed to be used with VR headsets and provide a more immersive experience by allowing users to walk or run in virtual environments. They typically have a circular design and feature a harness that holds the user in place while they move. Some VR treadmills also have sensors that detect the user's movements and adjust the virtual environment accordingly.

Haptic feedback devices are another type of VR accessory that provide tactile feedback to users. These devices are designed to simulate touch sensations and can be used to enhance the immersive experience of VR. For example, a haptic glove might provide feedback when the user touches a virtual object, making it feel more realistic.

Other VR accessories include eye-tracking devices, which track the user's eye movements and adjust the virtual environment accordingly, and wireless adapters, which eliminate the need for cables and make it easier to move around in virtual environments.

- Comparison of Virtual Reality Hardware and Software:

Virtual Reality (VR) technology consists of both hardware and software components that work together to create immersive experiences. The hardware includes the VR headset, controllers, and other accessories, while the software includes the applications and programs that run on the headset. When comparing VR hardware and software, there are several factors to consider, including performance, compatibility, and ease of use.

In terms of performance, VR hardware plays a critical role in creating a smooth and immersive experience. A high-end VR headset with powerful hardware can provide higher resolution, faster refresh rates, and more accurate tracking than a lower-end headset. Similarly, controllers with advanced features such as haptic feedback and motion tracking can provide a more natural and intuitive interaction with virtual environments. On the other hand, VR software plays a critical role in creating the content and experiences that users interact with. High-quality VR software can provide realistic and engaging virtual environments, while poorly designed software can lead to glitches and other issues that can detract from the overall experience.

Compatibility is another important factor to consider when comparing VR hardware and software. Not all VR headsets and controllers are compatible with all VR software, and vice versa. Some VR hardware may require specific software or drivers to function properly, while some VR software may only be compatible with certain hardware configurations. Additionally, compatibility issues can arise when using third-party accessories or software with VR hardware or software. As a result, it is important to carefully research compatibility before investing in VR hardware or software.

3.2 Data analysis techniques

3.2.1 VR on-site construction monitoring

The proposed computational framework enables real-time and remote monitoring of construction projects using a teleoperated quadruped robot as an on-site agent for the remote inspector. It consists of four main components: (a) robot control for remote navigation and control of the quadruped robot, (b) an AR model for comparing the live as-built status of the job site with the as-planned 3D geometric model of the building from its BIM, (c) a 2D floor plan for dynamic localization of the robot on the job site, and (d) live streaming 360° video of the construction site for panoramic and live visualization of the job site. This system saves time and travel costs by allowing project stakeholders to remotely monitor construction progress in real-time without needing to visit the site in person.

Traditionally, project stakeholders perform construction progress monitoring through in-person site visits, which is time-consuming and expensive. To address these challenges, a computational framework has been proposed for real-time and remote monitoring of construction projects using a teleoperated quadruped robot. The framework includes an AR solution that provides real-time visual feedback of the construction work compared to the 3D geometric model of the building from the BIM model. The framework was evaluated in two use cases and showed potential for remote construction progress monitoring work. However, the current scope of the study is limited to the geometry, colors, and textures of the building elements extracted from the BIM model.(Halder, Afsari, Serdakowski, DeVito, & Ensafi, 2022)

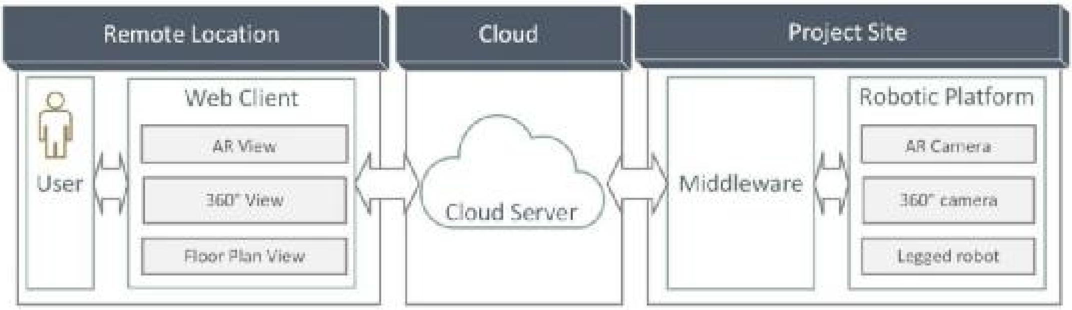

Fig. 10: Computational framework for a remote and real-time construction progress monitoring system using AR and Quadruped Robot

A new system has been developed to monitor and display the progress of construction on site. This system uses augmented reality (AR) to overlay a virtual building information model (BIM) onto the real-time scene of the construction site. The system utilizes simultaneous localization and mapping (SLAM) technology, which is based on visual-inertial odometry and point cloud map construction, to provide real-time positioning. By scanning the 3D environment and using a plane detection method, the system first establishes indoor positioning. A virtual BIM component is then attached to the corresponding real component at the actual site environment, with alignment ensured by setting it up on the centerline.

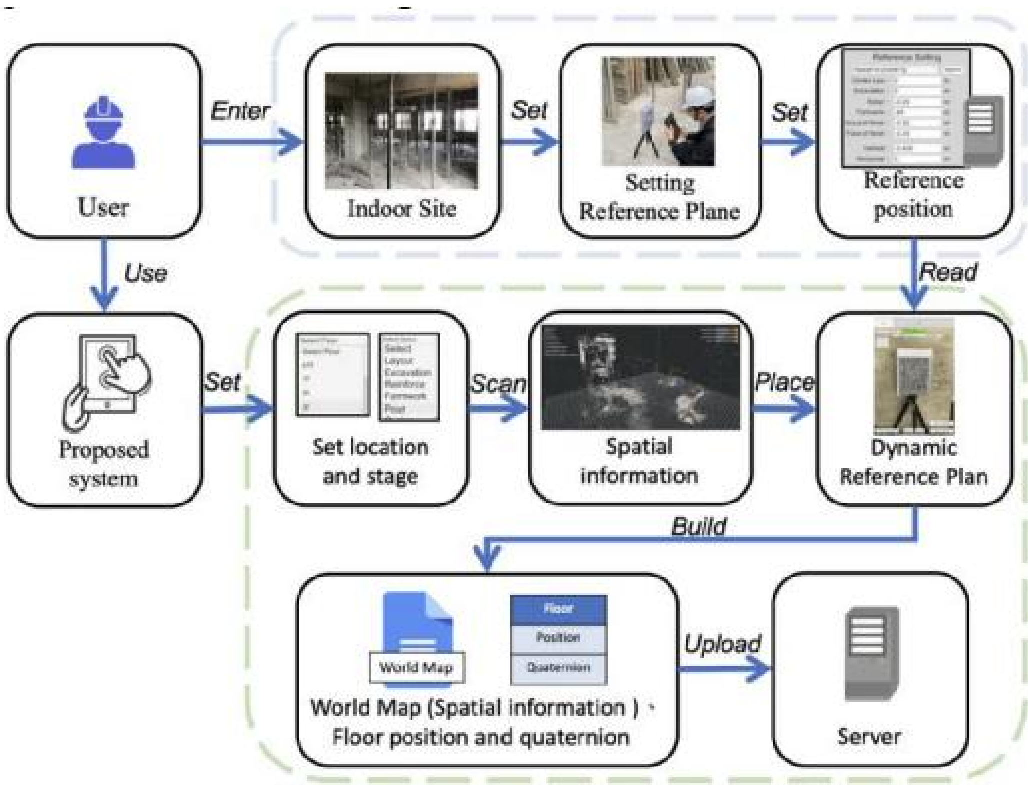

Fig. 11: The pre-setting process

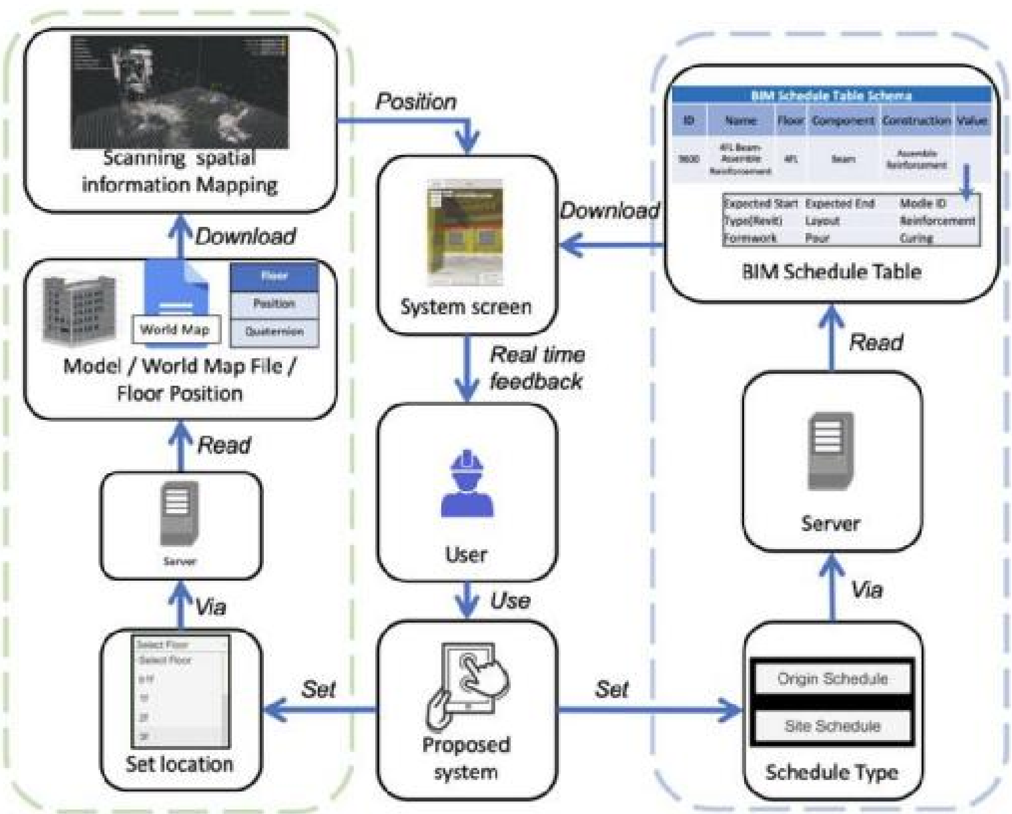

Fig. 12: The operating process

In order to create the "construction progress integration management system based on augmented reality technology," the system must first create a BIM model using 2D illustrations. After analyzing the project's scale, characteristics, management organization, management method, and work breakdown structure diagram of the RC structure, the system will be able to provide visual feedback to users based on the floor level when it is in operation.

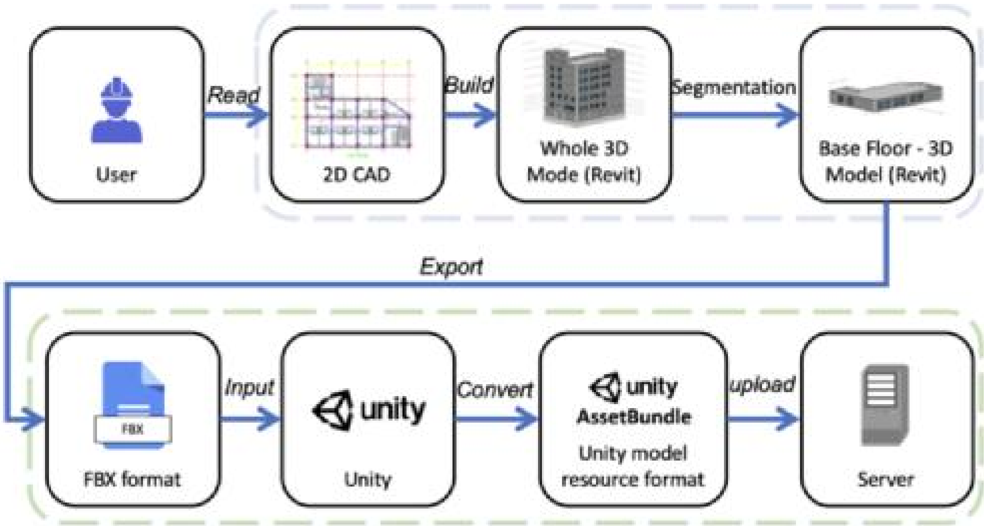

Fig. 13: The pre-setting process of the BIM model

This application has two modes: the first is used for presentation before the construction of a structure begins. The main goal of this mode is to minimize the ecological impact from the project site by investigating countermeasures for possible affected locations, such as adjacent houses, slopes, roads, and other existing structures. By using augmented reality, the system can provide a visualization of the construction disturbance range, such as construction access roads, earthwork, and material stacking areas, to determine the project configuration and for moving line planning. The system can also assist in confirming whether the depth after excavation is sufficient during construction and can help confirm the location of completed components on the site. Through repetitive detections of the augmented reality, the system can reveal any potential problems in advance and determine whether the original design or construction plan needs to be further adjusted. For the case study introduced in this research, the system was used to investigate slopes and existing channels surrounding the future water collecting well. (Wang & Chen, 2020)

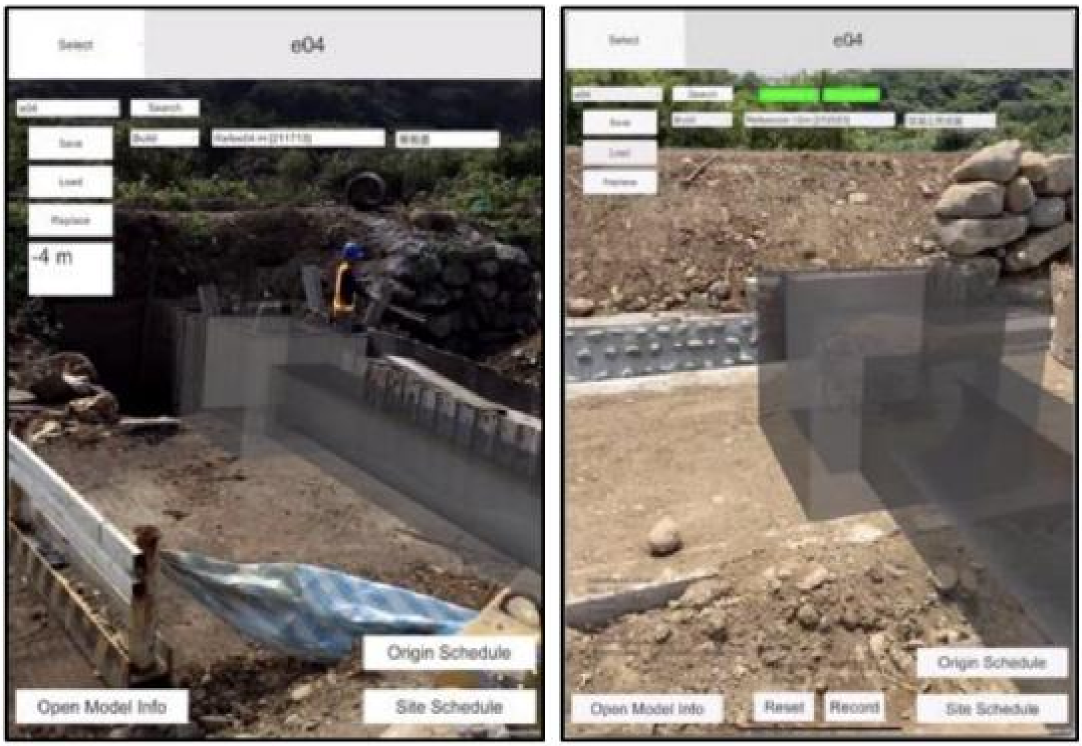

Fig. 14: Investigating the elevation of the water collecting well.

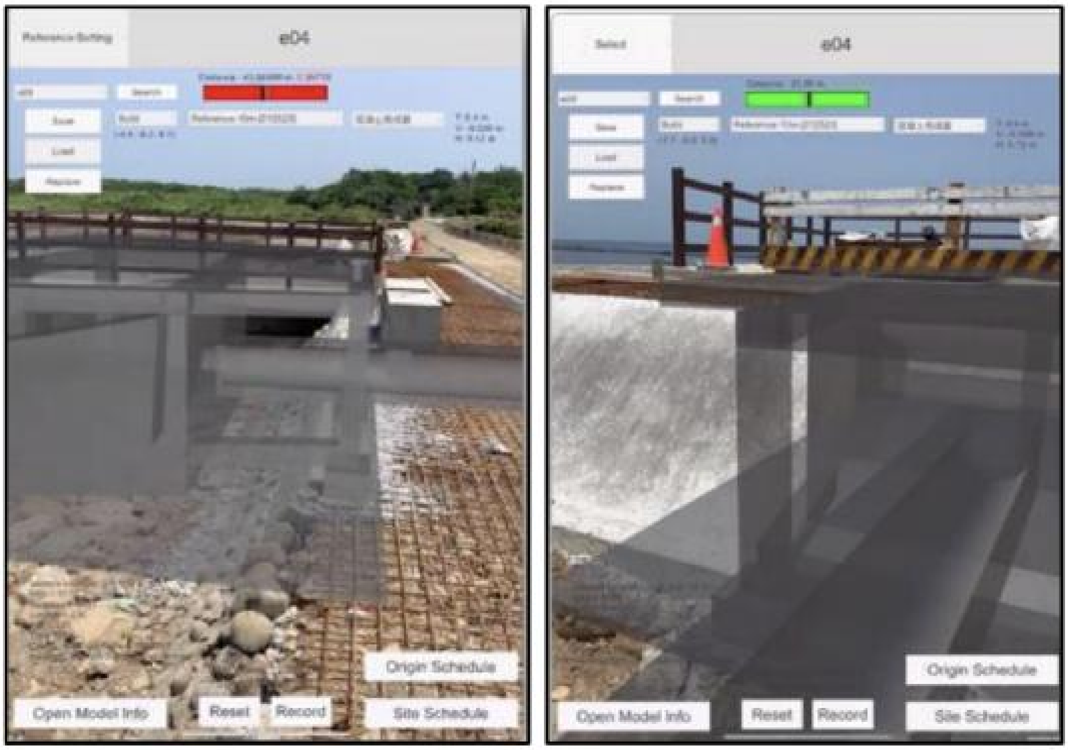

Fig. 15: Excavation depth confirmation on the construction site

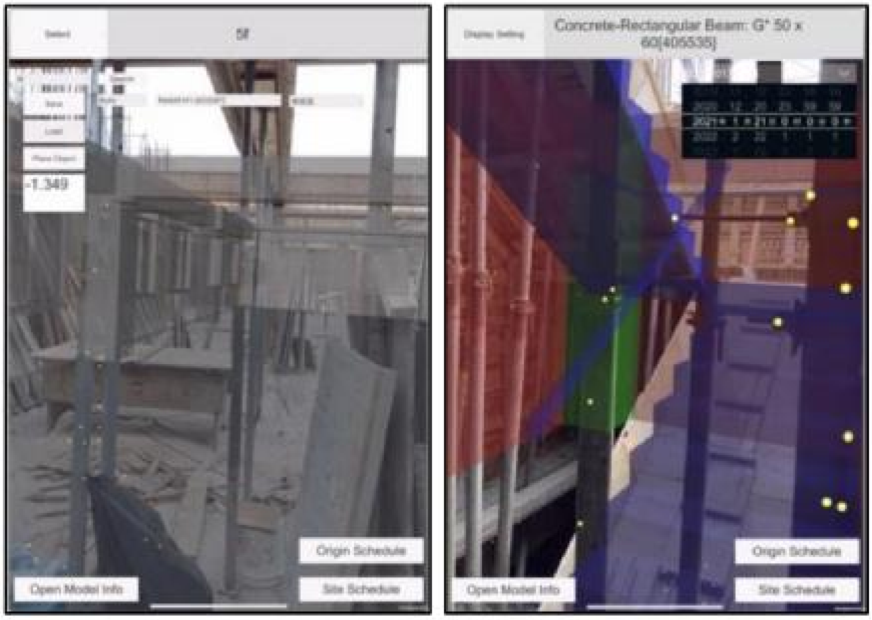

Fig. 16: Indoor location assistance for the structure construction

3.3 Ethical considerations

The use of virtual reality technology in designing and construction projects presents several ethical considerations.

Firstly, the use of virtual reality can raise issues of data privacy and security. When users interact with virtual environments, they may be providing sensitive information, such as personal or proprietary data, which must be adequately protected.

Secondly, there is the potential for virtual reality simulations to cause harm or distress to users, especially in cases where the simulations involve hazardous or traumatic scenarios. Care must be taken to ensure that users are adequately prepared and supported when engaging with such simulations.

Thirdly, the use of virtual reality can also raise concerns about accessibility and inclusivity, as some users may experience difficulty accessing or using the technology. It is important to ensure that virtual reality experiences are designed to be accessible to all users.

Finally, there are broader societal implications of the use of virtual reality in designing and construction, including issues related to the displacement of workers or the impact on local communities. It is important to consider these implications and to work to minimize any negative impacts.

Overall, the use of virtual reality in designing and construction must be accompanied by careful ethical considerations to ensure that the technology is used in a responsible and equitable manner.

One example of ethical considerations can be seen in the use of virtual reality to simulate hazardous scenarios in worker training programs. In such cases, the use of virtual reality raises concerns about the potential for harm or distress to users if the simulations are not adequately prepared or supported.

4. CASE STUDIES

4.1 Virtual reality in construction planning and design

4.1.1 Heavy Mobile Crane Planning for Modular Construction

Effective management and planning of resources are crucial in construction projects management, particularly in industrial projects that utilize offsite construction methods such as modularization. Modules, which are prefabricated elements assembled in module yards and shipped to the site for installation, require heavy mobile cranes as the main lifting machinery during installation. However, heavy mobile cranes are expensive and have a limited availability, emphasizing the need for precise planning and control. Proper use of heavy mobile cranes can reduce costs and speed up the construction process, while inappropriate operation can lead to overruns, delays, and safety issues. Traditional heavy lift path planning methods are ineffective and time-consuming, whereas computer-based simulation and visualization can be useful tools. The development of graphical computer aid modelling and interactive hardware provides an opportunity to facilitate training and learning in virtual environments (i.e., virtual reality, augmented reality, and mixed reality) in the architecture engineering and construction (AEC) industry. The use of VR technology can provide useful extra information and improve collaboration between operators, planners, and engineers to improve the plan. (Kayhani, Taghaddos, Noghabaee, & Hermann, 2018)

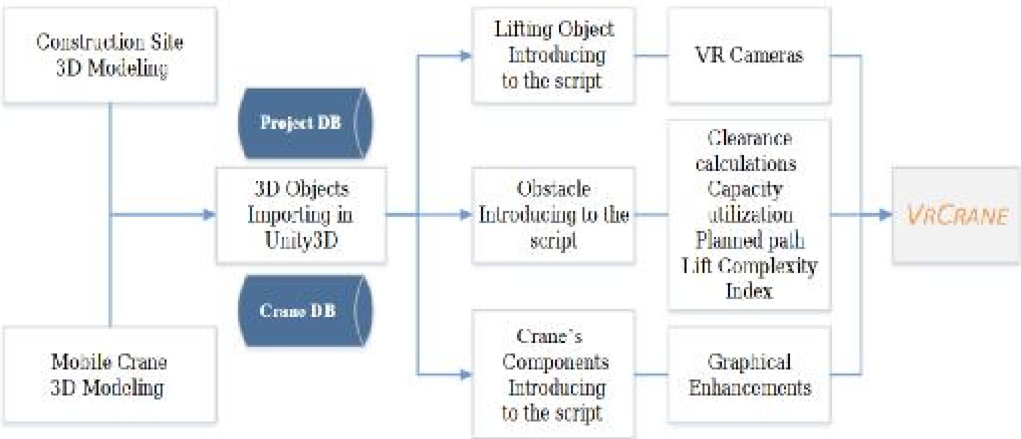

Fig. 17: VR-Crane Development System

Figure 4 shows an overview of VrCrane, a virtual reality (VR) simulator designed for heavy mobile cranes. To create this VR tool, the authors followed five main steps. First, a 3D model of the construction site and the selected crane is needed. This can be achieved by using Building Information Modelling (BIM) models or a raw 3D model and a manual database. For this project, the authors used a pilot BIM model of an industrial plant that contained both information and a 3D model. Second, users must be able to control every possible degree of freedom of the mobile crane. In the VrCrane simulator, different virtual cameras are used to provide users with a realistic experience of the lifting operation. These cameras allow users to view the operation from different angles, such as an operator's view, a signalman's view, or other views that are easily accessible in a virtual environment, such as bird view, plan view, and dynamic view. The simulator also includes real-time calculations and information presentations, such as capacity usage percentage, clearance color-coding, and risk evaluations, to increase the common understanding and facilitate communication among all decision makers and key stakeholders. (Figure 18) (Kayhani, Taghaddos, Noghabaee, & Hermann, 2018)

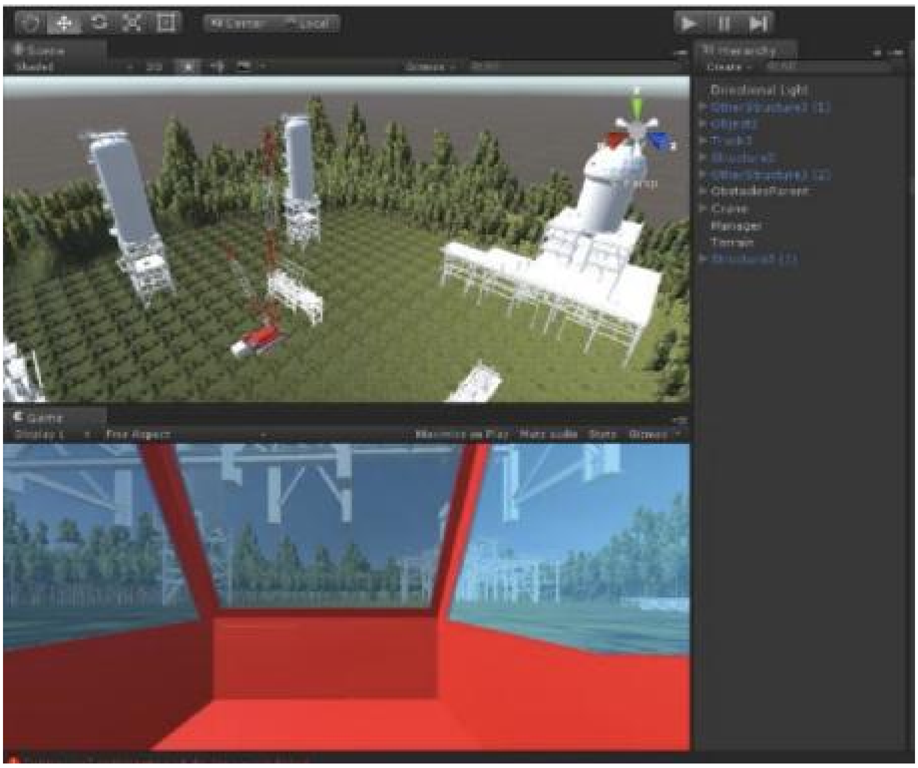

Fig. 18: Unity3D Simulation Environment

4.1.2 Implementation of Virtual Design and Construction: A Case Study in an Egyptian Construction Company

This study introduces a framework for using Virtual Design and Construction (VDC) in the construction industry. The aim is to explore the potential of virtual reality (VR) in construction, using an office building project as a case study. The following applications of VDC were utilized:

- VR 4D Simulation and Tracking:

The VR 4D simulation and tracking application involves linking project schedule activities to corresponding elements in the 3D model to visualize how the project will progress. This approach allows for immersive VR simulations, which provide a clear understanding of project activities compared to standard Gantt charts. A colored legend can be added to the simulation to display the category to which in-progress elements belong (i.e., Structure, Architecture, Mechanical, etc.).

During the simulation, time dimensions can be stopped to observe completed works and in-progress activities at a specific date. Cross-sections throughout the simulation can facilitate efficient progress tracking of all project elements. This approach enables the planned progress of concealed elements at a certain time to be viewed. Additionally, stakeholders can compare the project baseline with actual progress using the VR flythrough. The elements' actual progress can be updated in the VR model to run a simulation comparing baseline versus actual progress. (Figure 19)

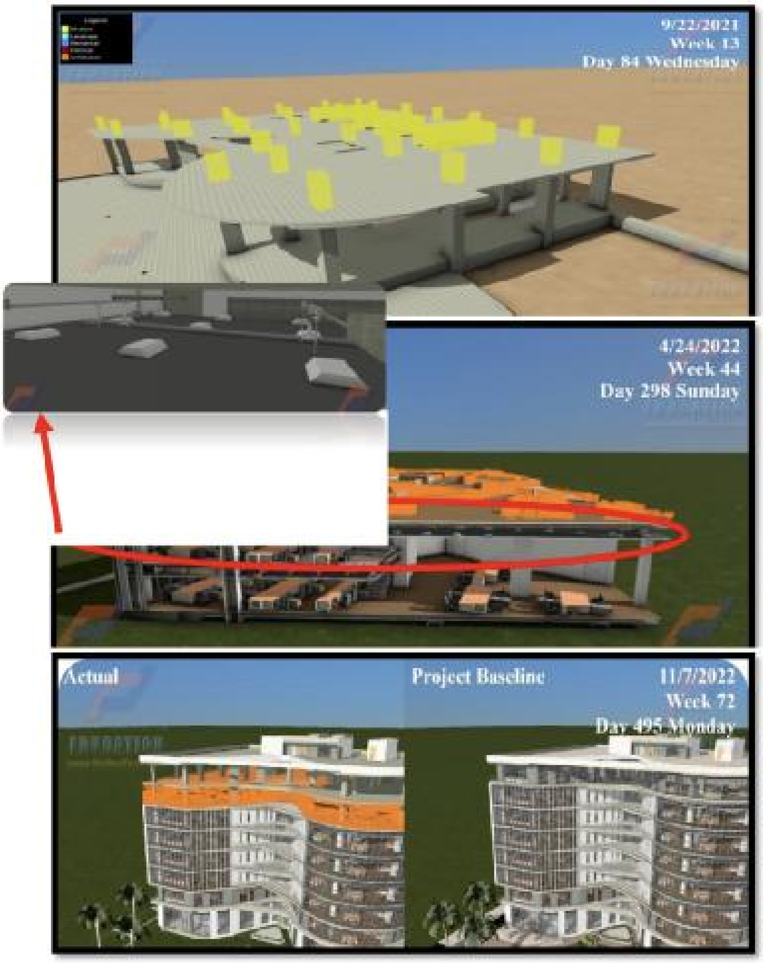

Fig. 19: A 4D simulation and tracking application in VR.

- Clash Analysis and VR Design Review:

Clash analysis is a tool used during the preconstruction and early construction phases to identify, locate, report, and resolve clashes of different elements before construction starts. Using VR, clashes can be further analyzed, and different approaches for clash resolution can be explored. The significance of VDC in clash analysis lies in the fact that some clashes displayed in the analysis may require no action. Additionally, pre-construction design review using VR can detect inconveniences that are not clashes. This may include design elements blocking passageways, door openings, light entrances, or HVAC supply louvers. (Fig. 19)

Fig. 20: An application for VR-based design review and clash analysis

- VR Real-Time Collaboration:

VDC can create a virtual world "Metaverse" that connects all project participants wherever they are located. This allows participants to exchange information in real-time through letters, emails, and meetings.

Fig. 21: An application for VR real-time collaboration

Eventually, the use of virtual reality (VR) in the construction industry has been gaining traction in recent years. A survey was conducted among industry professionals to evaluate the impact of VR implementation in construction, specifically through virtual design and construction (VDC). Results show that VR has a high to very high impact on various project objectives, including identifying design issues and clashes, reviewing designs pre-construction, improving coordination, and ensuring client satisfaction. Additionally, VR can aid in identifying design conflicts and construction challenges early on, leading to potential cost and time savings. However, the survey also highlighted some limitations, such as a lack of technology background and awareness, resistance to change, and high initial implementation costs. Employers, contractors, and consultants provided positive feedback on VR implementation, indicating a possible transition from traditional building information modelling (BIM) workflows to VDC workflows in the future. (S. Bakhoum, A. Younis, K. Aboulata, & R. Bekhit, 2023)

4.2 Virtual reality in sustainability and environmental design

4.2.1 A case study of Virtual Reality and Environmental Sustainability in the Automotive Industry

- Methods:

This case study explores the feasibility of using virtual reality (VR) technology in manufacturing to reduce environmental impact. Specifically, it draws on a case study in which a VR demo was developed to facilitate design reviews between a technology centre in Sweden and a manufacturing site in China. By using the VR demo, the company was able to reduce travel frequencies, as confirmed by user experience feedback and focus group discussions. The study shows that using VR for design reviews can contribute to environmental sustainability in the manufacturing industry.

VR facilities typically use one or more of the following five categories of setups: desktop systems, large projection screens (i.e., power walls), multiple connected projection screens (i.e., CAVE systems), stereo-capable monitors, and head-mounted displays (HMDs). At the heart of VR is the human experience, as it aims to simulate how we perceive the world through our information processing system and convince us that we are physically present within the virtual world.

The case study focuses on the development and testing of a VR demo in an automotive company with research and development centres in Sweden and manufacturing plants in China. The company was motivated to develop and implement VR technology to bridge the different teams and the case study aimed to demonstrate the advantages of adopting a multi-user VR system in interaction design. The VR demo was developed in close cooperation with the company using 3D laser scanning technology to capture input data and Unity3D as the development platform to integrate different data sources. The demo was tested in multiple phases, including a pilot test with colleagues from Gothenburg in Sweden and Gaithersburg in the United States, a second test in Sweden with external participants, and a final test in the case company in Gothenburg with 14 participants from different departments. Feedback was collected through a scale-rating survey regarding their testing experience, and 15 interviews were conducted to identify the most potential areas for VR implementation in the case company. The collected data was discussed and reviewed with the company at each key stage to avoid bias and misunderstanding.

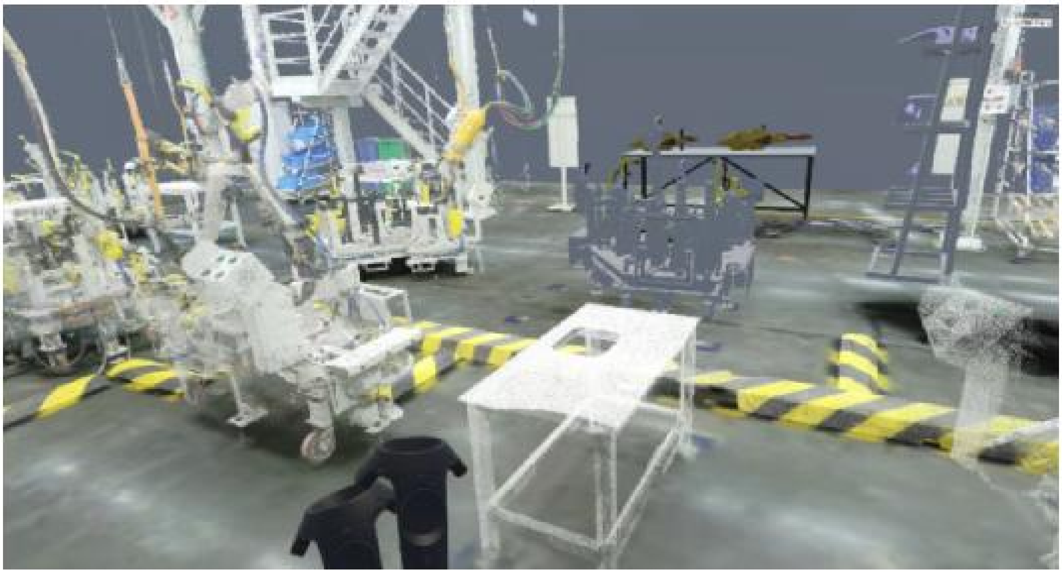

Fig. 22: The VR demo perspective from the initial version

Following the testing feedback and the interview results, a focus group discussion was held with the engineering department to discuss the biggest potential of VR application contributing to environmental sustainability. The summary of the discussion was used as an input to design a questionnaire for verification, in order to collect feedback from a broader scope of users. The questionnaire was designed with three parts: general information, questions regarding traveling and other influences from immersive VR, and insights about other possible impacts of using VR. The collected data was also reviewed with the company to avoid bias and misunderstanding. The results showed a reduction of travel frequencies for design review, thus contributing to environmental sustainability. The study highlights the feasibility of developing VR technologies to reduce environmental impact in the manufacturing industry.

- Results:

The paper presents findings from a case study conducted in several phases. The first phase involved the development of a pilot version of a VR demo that featured a realistic representation of a manufacturing environment in China. The demo was tested with colleagues in the U.S. and external partners in Sweden, and the potentials for further improvement were identified. Based on the feedback received, a second version of the demo was developed, which performed better and had improved synchronization and stability.

In the second phase, interview results were analysed, and 17 potential areas of VR application were identified within three main areas: Analysis, Communication, and Visualization. These areas were described as being connected to analysing ergonomic issues, enabling better communication, and visualizing matters and issues to enhance understanding, respectively. Most of the activities could be done with standard VR equipment that is available today at the case company, while some marked in yellow require planning and will be in place within a year.

Analysis	Communication	Visualization
Assembly geometry assurance	Claim support	Concept verification
Ensure safety of operator	Collaboration	Experience cell layout
Equipment verification	Create work instructions	Experience factory layout
Ergonomics	Discussions	Experience line layout
Reachability	Meetings	Perceived quality
Study processes	Status reporting	

In addition to the identified areas of VR application, the case study also revealed the need for long-distance communication between the company's locations in Sweden and China. Some interviewees reported that technical discussions through screen sharing can sometimes limit communication quality, which leads to a need for business trips. These trips mainly occur to ensure understanding between different parties, especially in areas of testing, such as car crashes, perceived quality, assembly precision, and production processes. Therefore, there is potential for VR to address these needs for long-distance communication and collaboration by providing a more immersive and interactive experience. (odu, Gong, Berce, Johansson, & Despeisse, 2021)

4.2.2 An Experimental Study in the Built Environment Domain

This study aims to investigate the relationship between 3D perception and presence in virtual environments. Despite the assumption in literature that more realistic virtual environments result in higher levels of presence, empirical evidence to support this is lacking. The research hypothesis is that there is an association between 3D perception and presence in virtual environments. The study conducts a controlled within-group experiment utilizing perception and presence questionnaires to test this hypothesis in two different virtual environments (non-immersive and immersive). Ultimately, the research aims to contribute to the understanding of the factors that promote presence in virtual environments and provide directions for developing and implementing more effective VR systems.

The method utilized in this study is a controlled experiment with a within-group experimental design. This design exposes all participants to both virtual reality (VR) systems to test the association between their 3D perception and presence responses in each condition. The within-subject design ensures that individual characteristics do not impact the results.

The study used a low fidelity Building Information Modelling (BIM) model in both VR modes to focus on technical specifications, rather than pictorial realism. The research team standardized participants' 3D perception responses in the VR conditions against their responses in the physical environment to observe the effects of display mode, stereopsis, field of view, and interactivity on 3D perception and presence. The VR modes included identical low-fidelity graphics/rendering effects and user interfaces. The non-immersive VR mode used a high-performance laptop, keyboard, and mouse for interaction devices.

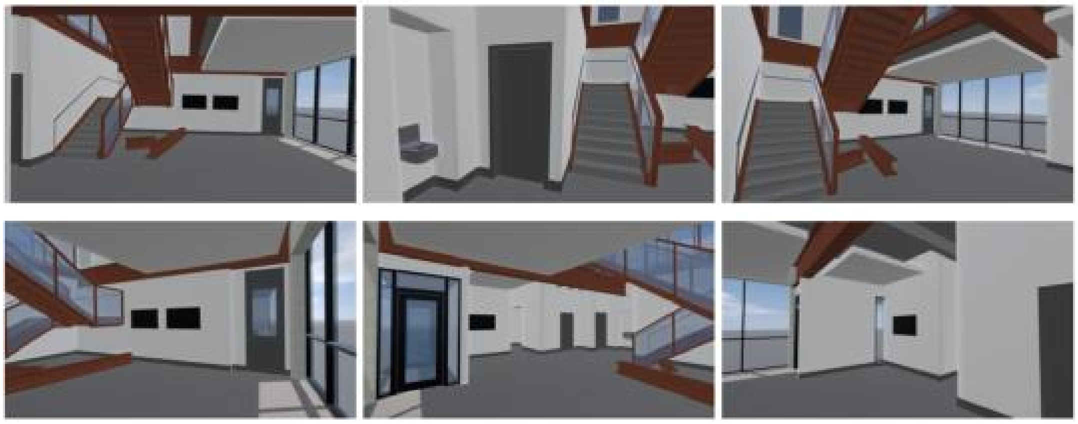

Fig. 23: The virtual environment

In summary, the current research method employs a within-group experimental design with standardized responses to collect user experiences in both VR modes. The use of low-fidelity BIM models in both VR modes ensures that technical specifications are met, and the use of a within-subject design controls for individual characteristics.

This research investigated the relationship between 3D perception and presence in virtual environments. The results indicate that incorporating advanced depth representation and visualization techniques may not necessarily contribute to highly immersive experiences. Instead, developers can focus on addressing other factors to promote engagement and presence, such as intuitive interaction methods. These findings have important implications for VR applications in the architecture, engineering, construction, operation and facility management sector and suggest that non-stereoscopic VR systems can still provide high levels of presence if other presence-promoting factors are included. (Paes, Irizarry, Billinghurst, & Pujoni, 2023)

4.3 Virtual reality in urban design

4.3.1 The Role of Urban Participation in the Field of Urban Design Using Virtual Reality

Public participation plays a crucial role in urban design as it allows for the involvement of the community in the development of their surroundings. It helps bridge the gap between officials and users by providing officials with a better understanding of the behaviour and culture of the users. Involving users in the decision-making process is essential as it ensures that their needs and priorities are taken into consideration and prevents the negative consequences of leaving decision-making solely to officials. Public participation is necessary in the modern world as it focuses on values such as environmental sustainability, economic viability, and social equity. It helps to discover solutions that provide comfort to development partners and meet public needs. By participating in different ways, both directly and indirectly, development partners can be trained to cope with their problems and work together to solve them. This helps to increase intellectual and cultural awareness, reduce gaps, and minimize social differences.

The proposed system aims to promote public participation through the use of virtual reality software called Vizard, which allows the creation of a three-dimensional model. The program offers various interactive decision-making methods, giving citizens the opportunity to explore the site and identify proposals that suit their needs. The system provides participants with the freedom to choose and express their opinions on the tool used by answering electronic questionnaires. The collected data generates content that can be used to make informed decisions, enhancing the exchange of opinions between decision makers and citizens and increasing the efficiency of the participation process. (See Fig. 24 for the main screen of the Vizard program.)

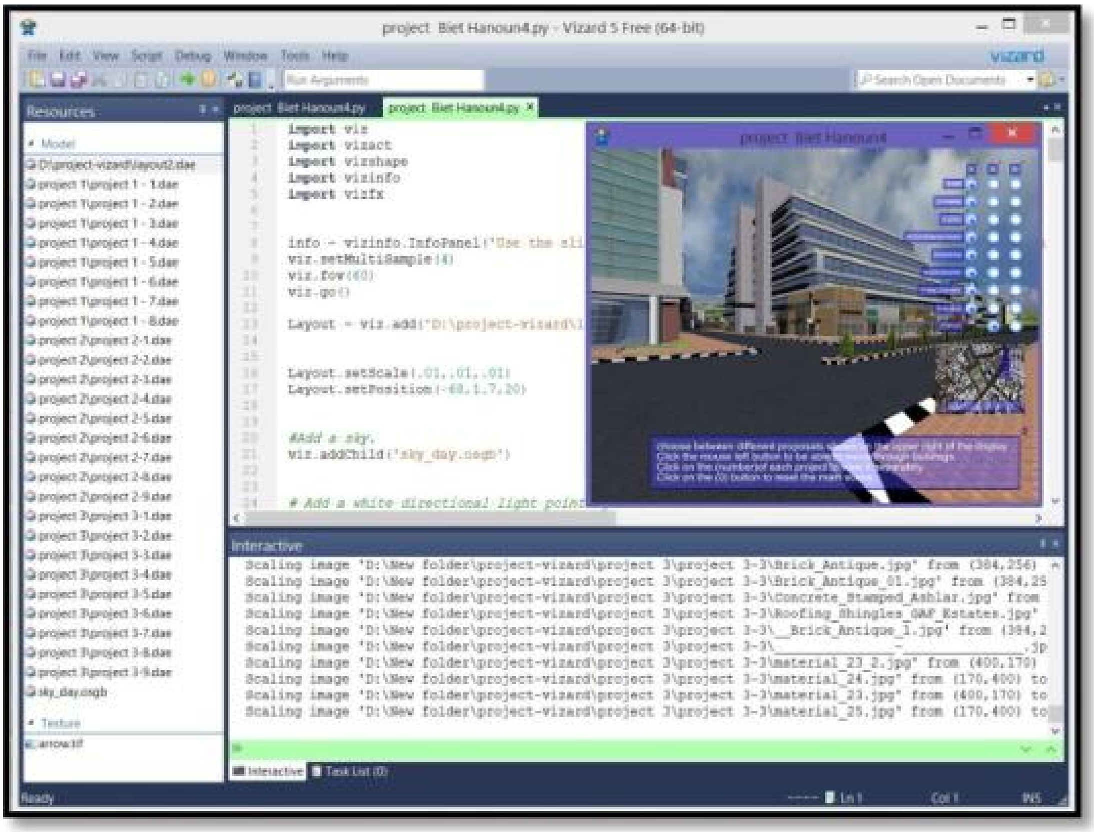

Fig. 24: The main screen of the Vizard program

In January 2017, a study was conducted in Beit Hanoun, Gaza, and Palestine to assess the process of public participation using virtual reality tools. The study aimed to test the tool with 30 citizens and decision-makers, 25 of whom responded. The process of participation included downloading interactive virtual reality files containing two models for viewing the proposals. The first had limited interactivity, while the second was highly interactive, allowing participants to freely choose between alternatives. An electronic questionnaire was also used to obtain feedback from participants, divided into four parts: introduction, identifying the participant's information, assessing the effectiveness of virtual reality tools, and evaluating the effectiveness of tools currently available in the city.

The evaluation criteria for the experiment included ease of use, cost of entry, target users, efficiency of the tool, interactivity, ease of communication, and satisfaction. The results of the study showed that the tool had a good level of completion for scientific participation, with the high-interactive view being easier to use. The cost of implementing the form and processing it for the process of participation was virtually nonexistent. Additionally, the tool's effectiveness was measured by the ability to attract citizens and the number of participants, as well as their absorption and the period of time to complete participation.

In conclusion, the virtual reality tool showed promise in the process of public participation. The tool was easy to use, cost-effective, and efficient in achieving its objectives. The study's evaluation criteria provided a comprehensive understanding of the tool's performance, and the results showed that it was well received by participants. These findings may be relevant for future research in the field of virtual reality and public participation, particularly in areas with limited access to physical participation. (Fares, Taha, & Sayad, 2018)

4.4 Virtual reality in construction safety and training

Virtual reality has been shown to be an effective tool for improving safety training in the construction industry. By using virtual reality simulations, workers can experience hazardous scenarios in a safe and controlled environment, allowing them to develop the necessary skills and knowledge to handle these situations in the field. Additionally, virtual reality can help improve the retention and transfer of safety training, as workers are more likely to remember and apply what they learned in a realistic and immersive environment.

4.4.1 An application for construction safety training

The construction industry experiences a high number of work-related injuries and fatalities, which makes safety a crucial concern. Traditional safety training methods such as video recordings, hand-outs, and hands-on training have their own advantages and disadvantages. Mixed reality technology, specifically virtual reality (VR), has been used in different aspects of construction and is a more immersive and realistic alternative compared to other training options. VR can simulate high-risk environments without putting workers at risk, making it an effective tool for safety training. Roofing workers, in particular, are at high risk due to their work conditions, and VR can simulate high-altitude situations without posing actual falling risks. However, most studies on VR technology in construction safety training have focused on effectiveness and not on the needs of end-users, specifically roofing professionals. Therefore, an industry-oriented approach was adopted in this study to develop a VR safety training program for roofing workers and to capture the industry's perception of VR training. The survey results show that exposure to VR training positively impacts industry practitioners, especially younger generations. This study contributes to the body of knowledge by providing a safety training module specifically for the roofing sector, which is more applicable to their routines than general safety training.

The purpose of the study was to assess the feasibility of using VR technology for safety training, specifically targeting roofing professionals. The methodology involved progressive elaboration, with industry inputs used to develop and validate different scenarios. Ten sections were designed to cover various ladder-related tasks, each assuming a new roofing worker who needs to evaluate safety risks. The VR application was optimized for Oculus Quest 2 headset and developed using the Unity game engine. Screenshots of different features of the VR application are presented in Figure 12. The study also aimed to evaluate user perceptions of the VR training module.

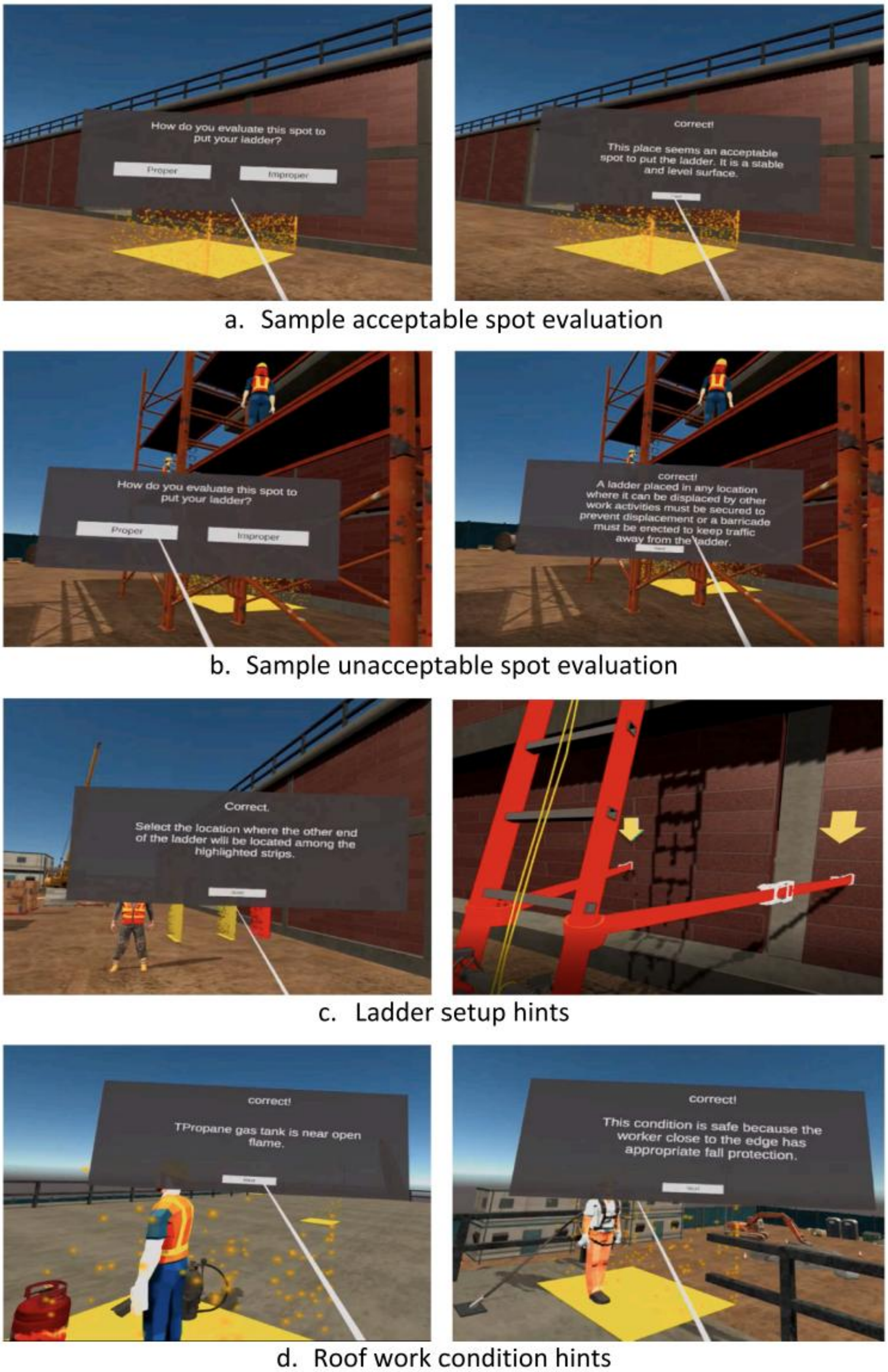

Fig. 25: Screenshots of the VR application interface

Industry experts were involved in testing each section of the VR application to ensure that the components and actions embedded in it were correct and applicable. The sponsoring organization, which is the primary professional organization for roofing contractors in the U.S., referred these experts to the research project. The researchers and the sponsor agreed that the sponsor representatives would be fully involved in the design and development processes, which led to the formation of the Task Force. This group was involved in quality control throughout the design and development phases, in addition to the internal review process. Once the beta version of the application was ready, the industry task force members invited their employees to use it and provide feedback via a survey. The survey used a Likert scale to measure the agreement levels of the users and collected responses for a 10-day period. A total of 46 valid samples were used in the analysis. The survey's internal consistency was rated as very good, with a Cronbach's alpha of 0.80 and 0.89 for the impacting factors and VR feature sections. (Rokooei, Shojaei, Alvanchi, Azad, & Didehvar, 2023)

4.4.2 A case study of Mitigating Costly Errors: The High Stakes of Tolerances in Hyperscale Data Center Construction

The construction industry has been plagued with a persistent problem - up to 80% of the completed construction work is found to be built out of tolerance, which leads to discovering errors only after incurring substantial costs. This issue is amplified in the case of hyperscale data center projects, which are complex and large facilities where mistakes are more likely to occur. Moreover, such projects have high stakes as any delays caused by errors can result in immediate revenue loss for the clients. The company has identified several issues, including the discrepancies between the 3D model and its implementation in construction, the difficulty in obtaining accurate root cause data, and the tendency of contractors to blame poor design while designers blame the lack of timely feedback from contractors.

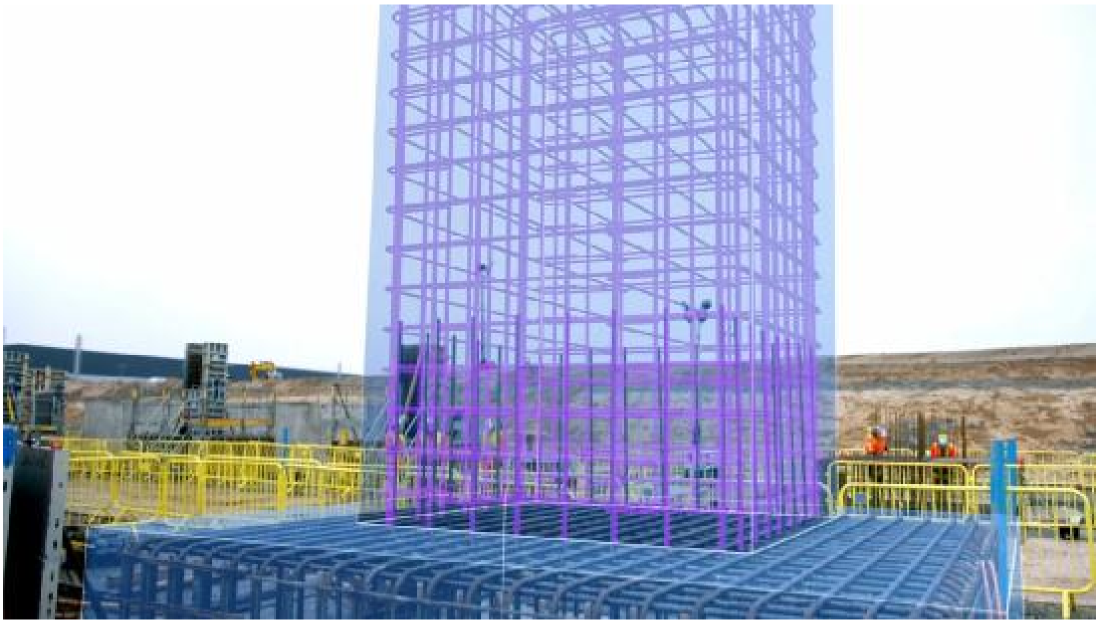

Fig. 26: Snapshot after Deploying Augmented Reality Headset (1)

To facilitate the coordination and construction of a $400m hyperscale data center, The Atom was deployed on site. To streamline inspections, ARQ workflows were implemented, which seamlessly linked with Autodesk's BIM 360 software, enabling real-time validation in the field. To ensure the accuracy of inspections and analysis of subsequent findings, an XYZ Field Application Engineer was stationed on site. As a recognized expert in digital integration and project delivery, engineering group aimed to enhance project-wide communication, proactively resolve on-site issues, and minimize the need for rework.

Fig. 27: Snapshot after Deploying Augmented Reality Headset (2)

The integration of AR inspections via an engineering Grade AR headset, the Atom, with Group's project management system, Autodesk BIM 360, resulted in a doubling of the number of inspections conducted on the project. However, the seamless interoperability of the software and the comparative ease of AR inspections ensured that the extra project control did not create undue pressure or increase time demands on project teams. Inspections were carried out throughout the project, from advanced coordination to construction and beyond. The Atom's technology proved to be particularly effective in identifying and proactively addressing issues during pre-installation, as well as on the complex mechanical and electrical engineering works of the data center. During the installation phase, the Atom was used to ensure that long-span equipment, such as walls or ductwork, remained on course. From the first deployment until just beyond the project's halfway point, a total of 489 early issues were identified and rectified using the Atom, thereby preventing additional costs and delays. (The Benefits of Using Augmented Reality in Construction, n.d.)

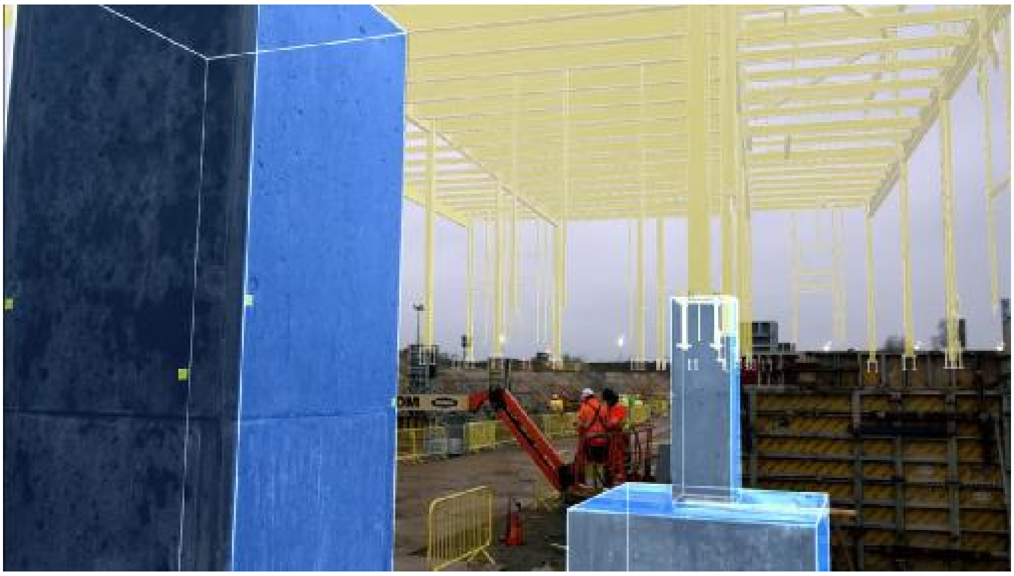

Fig. 28: Snapshot after Deploying Augmented Reality Headset (3)

4.4.3 A case study of identifying mechanical equipment setting-out errors with Augmented Reality

The project described in the case study was the construction of a pharmaceutical plant in Ireland, with a value of $150 million and a size of 10,000 square feet. The project involved the installation of large mechanical and electrical equipment, which are resource-intensive and require careful coordination to avoid errors during installation. The Atom was deployed by the main contractor's mechanical package manager to inspect a key HVAC location and ensure that AHUs and dehumidifiers were being installed correctly and without clashes with upcoming interfacing ductwork. Thanks to the use of the Atom, a setting-out error was identified and corrected before critical lifting equipment was removed, saving both time and money on the project.

- Problem:

Installing large mechanical equipment is a complex and resource-intensive task that requires a high level of coordination. Any errors made during installation can have serious consequences, including site disruptions and costly rework. This was the challenge faced by a pharmaceutical plant in Ireland, where a mechanical package manager for the main contractor deployed The Atom to inspect a key HVAC location.

- Scope:

The inspection was used to assess the installation of air handling units (AHUs) and dehumidifiers to ensure they were in the correct location and didn't clash with upcoming interfacing ductwork. The installers used 2D drawings to set out and position the two dehumidifiers in the area, but the drawings did not contain all the relevant information. As a result, the team installed the dehumidifiers in the correct footprint but in the opposite orientation, which could have led to critical lifting equipment being removed and interfacing works being installed incorrectly.

- Result:

With Augmented Reality Headset, the mistake was identified and corrected before critical lifting equipment was removed and interfacing works were installed. The Main Contractor and the sub-contractor team were able to rectify the error quickly and efficiently, saving valuable time on the schedule and rework costs from the budget. The inspection not only ensured that the dehumidifiers were installed correctly, but it also prevented potential delays and disruptions to the entire project. The Augmented Reality Headset's ability to detect errors in real-time helped to ensure that the project was completed on time and within budget. (XYZ Reality, n.d.)

Fig. 29: Identifying mechanical equipment installation errors using Augmented Reality technology.

4.4.4 Using AR to Ensure Precision in Prefabricated Construction: A Case Study

The case study is about a hyperscale data center project in the Netherlands. The project involves the installation of prefabricated concrete chambers, which were to be built offsite and delivered onsite for installation. The project owner and the main contractor selected XYZ Reality's Engineering Grade AR™ headset, the Atom™, to ensure the highest levels of project accuracy onsite, real-time visibility of works, and access to crucial data.

- Problem:

During the installation of the prefabricated concrete chambers, an XYZ Field Application Engineer (FAE) identified a number of major issues. The Atom revealed that the prefab chambers supplied by an external manufacturer did not match up with the intended design, resulting in misalignment with what was required, significant rework, and delays for the subcontractor responsible for installation. Unfortunately, this error was not identified by project teams until XYZ Reality arrived onsite, at which point three of the concrete chambers had already been installed incorrectly. This design deviation caused delays in the installation of the pipe and required additional insulation work, leading to almost two months of delay in the project.

- Scope:

The scope of the problem was to identify the deviation in the design and rectify the position of the prefabricated element to ensure project accuracy and eliminate errors. The scope also included improving communication and follow-up processes between the owner, project team, manufacturer, and subcontractor to avoid similar errors in the future.

- Solution:

The solution was to deploy XYZ Reality's Engineering Grade AR solution onsite to ensure precision in prefabricated construction. The solution allowed the XYZ Field Application Engineer to inspect the prefabricated chambers and identify the design deviations before installation. The solution also improved communication and follow-up processes between the project teams and the subcontractor to avoid similar errors in the future. The solution helped to build trust between XYZ Reality, the project teams, and the subcontractor, ensuring the highest levels of project accuracy, real-time visibility of works, and access to crucial data. The solution helped to eliminate errors and ensure timely delivery of the critical infrastructure project. (XYZ Reality, 2023)

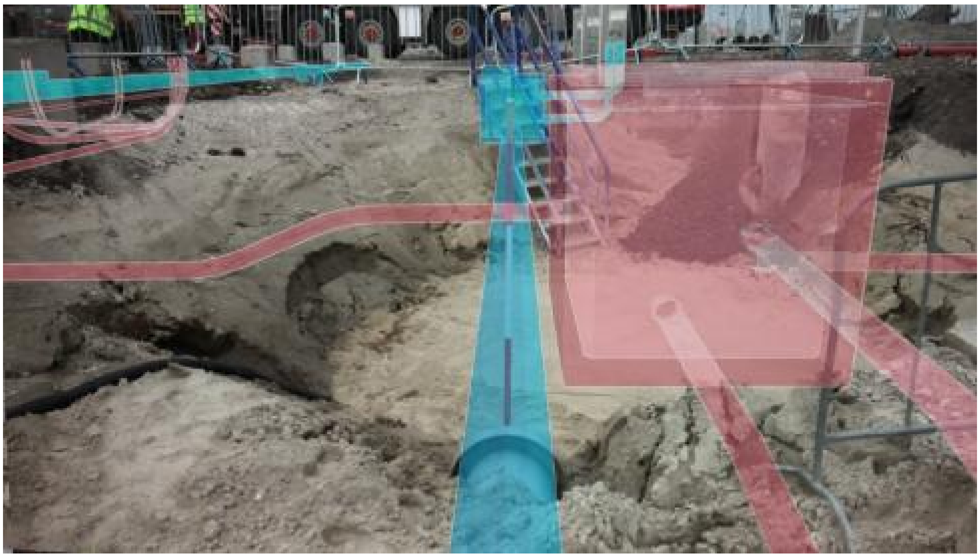

Fig. 30: The installation of the prefabricated concrete chambers (1)

Fig. 31: The installation of the prefabricated concrete chambers (2)

4.4.5 A case study of Onsite Prefabricated Inspections

- Problem:

The shift towards modern construction methods involved prefabricated elements and factory witness testing, which became critical in the construction process. However, the COVID-19 pandemic created travel restrictions, making regular factory visits infeasible, and creating a risk to health and safety during inspections.

- Scope:

To overcome the constraints and restrictions created by the pandemic, the Main Contractor and XYZ Reality collaborated to redefine Factory Witness Testing procedures. This involved bringing the Factory Witness Testing to the site by creating a designated inspection zone, remote streaming the inspection captured by The Atom AR headset, and incorporating interfacing elements into the inspection.

- Solution:

During one of the first deliveries of a prefabricated fiber cable chamber, the site teams quickly identified two errors by viewing models of the chamber and the interfacing ductwork. The errors included a base of concrete 200mm too wide and misaligned ductwork openings by 75mm. By catching this error quickly, the chamber prefabrication was reconfigured to the correct dimensions, avoiding future installation errors and rework. Additionally, all relevant package managers and trade contractors could validate or reject the inspection through the live streaming capabilities of The Atom. The solution led to significant construction rework savings, time savings for prefabrication, and cost savings due to delays to groundworks impacting ductwork installation. The success of the inspection led to the main contractor requesting that all underfloor services in the area be set out using XYZ. The project took place in Denmark, in the data center industry, with a value of €300M and a size of 40MW. (XYZ Reality, 2023)

Fig. 32: Onsite Prefabricated Inspections

4.4.6 A Case Study of Virtual Reality Serious Games for Earthquake Preparedness

The aim of this case study is to explore the potential use of Virtual Reality (VR) and Serious Games (SGs) in enhancing earthquake preparedness for building occupants. The paper provides a theoretical discussion on the advantages and limitations of using VR SGs to investigate the behavior of occupants during earthquake evacuations and to train them to cope with such emergencies. The authors also discuss key design components for developing a VR SG framework and present the Auckland City Hospital in New Zealand as a case study to illustrate the potential use of VR SGs in public buildings. The ultimate goal is to enhance evacuee safety and reduce the number of injuries and deaths resulting from earthquakes.

Traditional evacuation drills have limitations and may not provide effective training. VR and SGs offer a more realistic and immersive experience, allowing for the representation of multiple threats, including building damage. The article aims to explore the advantages and limitations of using these technologies to train building occupants and improve post-earthquake evacuation preparedness. The paper presents a case study of developing two VR SG prototypes to investigate human behavior during an earthquake and teach users the best earthquake evacuation practices.

The case study describes the development of two prototypes, the Behavioural Prototype (BP) and the Training Prototype (TP), designed to study human behavior during earthquake evacuations and to train users on earthquake safety practices based on the New Zealand Civil Defense guidelines. The prototypes were developed using virtual reality (VR) serious games (SGs) and were created by a team of researchers with diverse backgrounds, including civil engineering, computer science, and social science, with input from public organizations such as the New Zealand Civil Defense and the Auckland District Health Board. The game location for both prototypes is a section of the Auckland City Hospital, chosen because it gives access to various building occupants such as staff and visitors. The 3D model of this section of the building was developed using BIM software tools and was optimized for the gaming purpose by using Lightmapping and Occlusion Culling algorithms to achieve an ideal target of 50 frames per second. This paper represents the first implementation of a serious game for post-earthquake evacuation training implemented in a hospital environment.

The earthquake was simulated by shaking the virtual room's floor in which users were located, and the earthquake code was selected to generate damage equivalent to the VII-VIII intensity of the Modified Mercalli Scale. The Unity physics engine applied virtual forces to the floor and objects in the room, considering the mass, static or kinematic friction coefficients, and sliding conditions of each object. The earthquake impact was only simulated in the areas where the participant was located due to computational demands, and the remaining parts of the building's impact was generated programmatically using a C# script. The building damage was also generated using a qualitative approach through a C# script that replaced the undamaged walls and ceiling with damaged walls and ceiling, and damage to boards and tiles was added during the earthquake stage. Finally, a chair shaking system was implemented for the VR experience, where users were seated on a vibrating platform activated by the earthquake noise generated during the game.

Non-player Characters (NPCs) are virtual characters in a game or simulation that are not controlled by the player. Their behaviors are predetermined by scripts, and they are used to populate the virtual environment to make it more realistic. There are two types of NPCs: non-interactive and interactive. Non-interactive NPCs are pre-assigned with roles such as staff, patients, and visitors, and they follow a typical daily routine. Interactive NPCs, on the other hand, are used to guide or accompany players and investigate social behaviors during building evacuations. NPCs are created and animated using various software packages and techniques, including Adobe Fuse CC, Adobe Mixamo, and Unity. To make NPCs more realistic, facial animations and assigned texts are added, and C# scripts and animation controllers are used to control their behaviors.

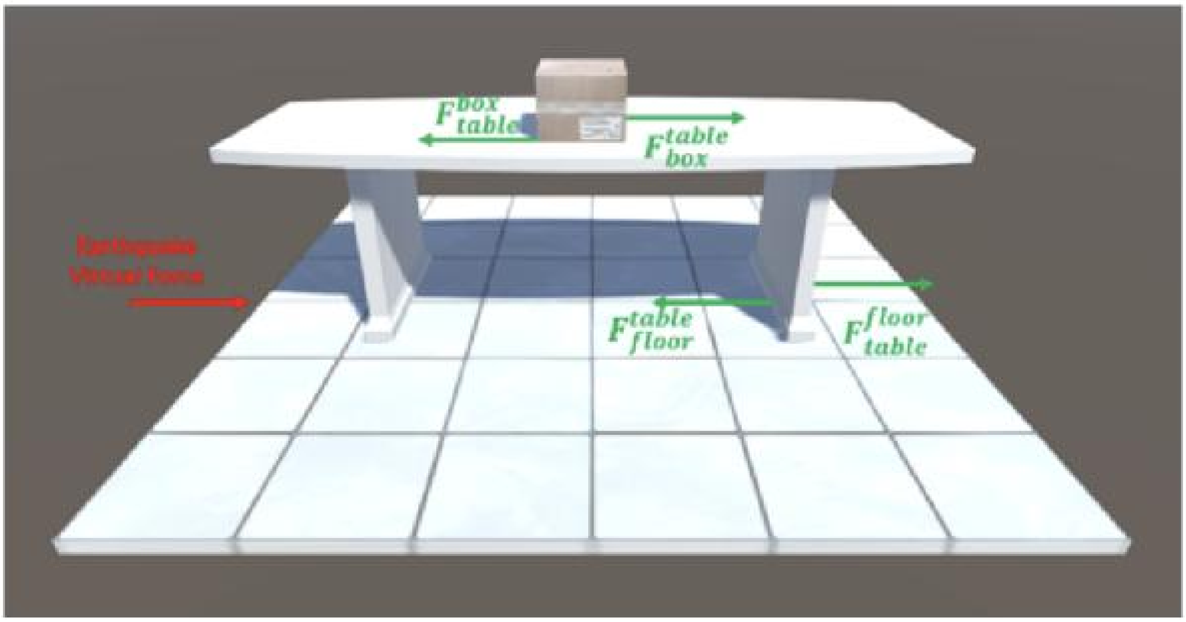

Fig. 33: Earthquake force propagation in the virtual environment

The VR navigation solution in the BP combines an open world solution and a first-person controller, allowing participants to move freely through the virtual world while following a designed storyline. To avoid motion sickness, teleportation is not used, but instead, participants can navigate towards the direction they are looking at by clicking a single button. They rotate with their full body accordingly, reducing the sickness as rotations in the virtual and physical environments are the same. To avoid the risk of falling while rotating on the shaking platform, participants sit on a rotatable chair giving them the possibility to rotate through a full 360°.

In the TP, the navigation solution is a combination of wait points and a first-person controller, taking participants through predefined scenarios following a planned order. Navigation between wait points is driven by a C# navigation script, and participants can choose actions by selecting among several action panels. The main limitation is that it reduces the possibility of participants to navigate freely, but this did not represent a concern for the development of the TP as it is mainly designed to generate learning outcomes rather than being a fully interactive environment.

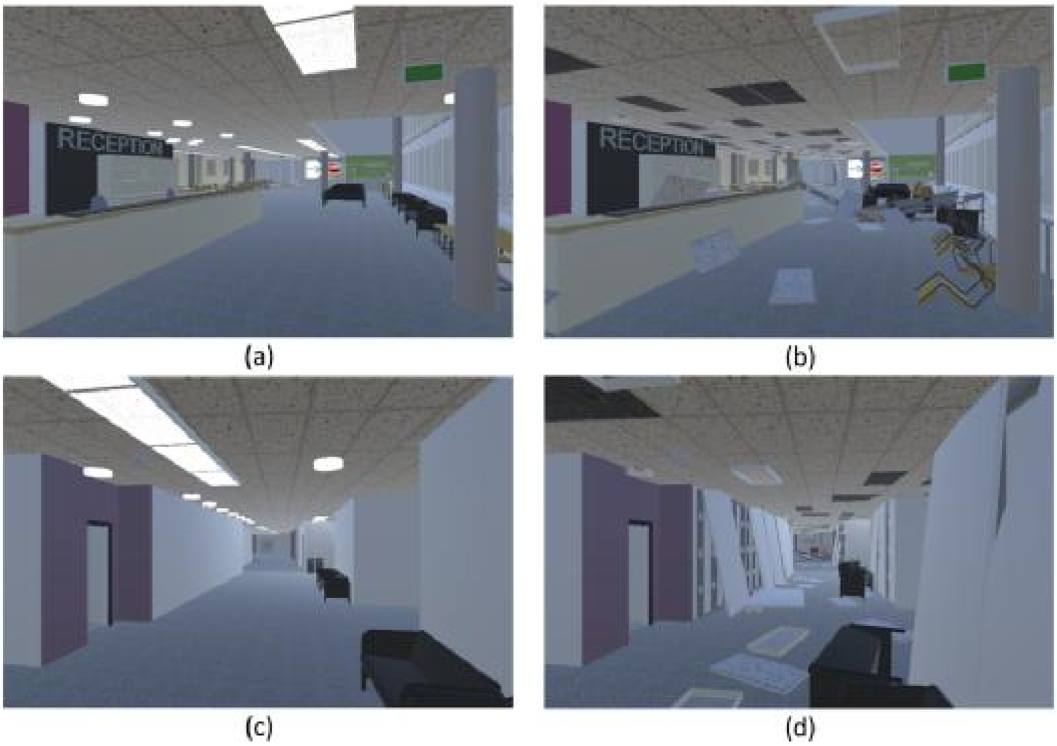

Fig. 34: Comparison between the undamaged environment (a and c) and damaged environment (b and d).

The proposed solutions for simulating an earthquake in a virtual building using the Unity physics engine were perceived as relatively realistic by the participants, and there was no significant difference in the perception of the two prototypes. However, the perception of non-player characters (NPCs) was relatively low, and the authors suggested the development of a second generation of SGs that included a more comprehensive interaction between NPCs and participants. The paper also identified two navigation solutions that had a high level of usability and minimal motion sickness and proposed that new VR SGs could benefit from their implementation.

The realism of the virtual environment and earthquake damage is the most significant factor in the overall level of sense of presence experienced by the participants and emphasizes the importance of designing SGs for earthquake emergencies that address the complexity of the evacuation procedure and include longer and more articulate storylines than those typically implemented in fire SGs. (Lovreglio , et al., 2018)

4.5 The use of VR technology in project management and scheduling

Virtual Reality (VR) technology has the potential to revolutionize the way project management and scheduling are carried out in the construction industry. By using VR technology, project managers can create immersive and interactive simulations that allow them to better visualize and plan construction projects. VR technology can be used to create a 3D model of the construction site, which can be updated in real-time as the project progresses. This can help project managers to identify potential issues and conflicts early on, allowing them to take corrective action before they become major problems. Additionally, VR technology can be used to create virtual mockups of construction components, which can be used for testing and quality assurance. By using VR technology in project management and scheduling, construction companies can improve their accuracy, reduce errors and rework, and ultimately deliver projects on time and within budget.

The spatial aspects of project development are important but often overlooked in traditional scheduling and progress control techniques like bar charts and the critical path method (CPM). This study focuses on how virtual reality technology can be used to visualize the spatial aspects of construction projects during scheduling and reporting. The passage also explains different scheduling methods, including the critical path method, linear scheduling model, and repetitive scheduling method, and their mathematical and graphical approaches. The use of singularity functions in the productivity scheduling method allows for an integrated treatment of activities regardless of the number of modifications in productivity. Overall, the passage emphasizes the importance of visualizing spatial aspects in project management to prevent costly errors and delays. (STRAND, 2020)

4.5.1 Exploring the Applications of Virtual Reality and Augmented Reality in Project Schedule Control: A Systematic Review

In the construction industry, project management and scheduling are critical aspects that require precise control and monitoring. However, many risk factors can hinder project progress and make it difficult for project teams to achieve predetermined schedules. In a recent paper, the authors address this issue by exploring how Virtual Reality (VR) and Augmented Reality (AR) can be used to visualize and understand the spatial aspects of a construction project. They argue that traditional methods, such as bar charts and the critical path method, lack the ability to provide detailed insights into the spatial aspects of a project, which can be crucial in identifying potential risks and controlling project progress.

The paper presents a review of existing literature on how VR and AR can assist in project schedule control, highlighting the importance of project participants being able to access and understand abstract and dynamic project information. By categorizing schedule risks into internal and external risks, the authors provide a comprehensive understanding of the challenges faced in project management and scheduling. The paper proposes the use of 3D project models that can offer visually detailed insights into the spatial aspects of a construction project, forming a graphical representation between the construction activities and the project model. This approach can help project participants to better understand the project and identify potential risks, ultimately leading to more efficient project management and scheduling.

- Enhancing Design Quality and Collaboration in Schedule Control through VR and AR

In the construction industry, poor design quality, design delay, and design change can pose significant risks to project schedules. This paper explores how virtual reality (VR) and augmented reality (AR) can mitigate these risks by supporting designers in visualizing design concepts, facilitating collaborative design, and speeding up design review.

VR and AR are effective design tools that offer a more immersive and detailed visualization of design concepts. They allow designers to better understand spatial relationships of design components and make selective reinterpretations of their design thinking. AR can help designers visualize designs in their physical environment, allowing for a better understanding of the context and proper placement of the building.

Collaborative design can also be improved with VR and AR, as they offer better communication and comprehension between remote team members. Tangible user interfaces (TUI) integrated with AR benefit designers' cognitive activities and design processes in co-located design collaboration. In addition, design reviews can be expedited with VR and AR, as they offer a more efficient and economical way to evaluate design options and identify potential design defects. Overall, VR and AR offer significant benefits in enhancing design quality and collaboration in schedule control, leading to improved project outcomes.

Owner involvement is crucial for managing project schedule risk, but it often needs to be improved in practical projects. Virtual reality (VR) and augmented reality (AR) can facilitate owner involvement due to their excellent visual effects and low professional thresholds. They are particularly useful in addressing the issue that owners often lack technical and professional knowledge in construction, which impedes their involvement. By facilitating owner involvement, VR and AR can benefit project schedule control in two ways. Firstly, they can help owners become involved in the pre-construction phase, which can improve the quality of design and planning and reduce changes during the construction phase. For example, VR and AR can allow owners to closely review designs in a virtual or physical environment and get a real sense of what construction production would be. Secondly, VR and AR can speed up the decision-making process for owners during project development and implementation, leading to timely decisions.

VR and AR are also potential tools to help contractors manage construction schedules. They contribute to schedule control through planning and scheduling, progress monitoring, improving labor productivity, and improving coordination among participants. In terms of planning and scheduling, many IT tools have been developed to support construction planning and scheduling by visualizing construction plans. VR and AR can provide a better simulation approach by mimicking or integrating real-world physical property in the computer and providing an intuitive, interactive interface to examine construction operations and processes. They are particularly appreciated for visualizing key points in construction to find the best construction scenario under the condition constraints, such as virtual construction and VR prototyping. However, simulation using VR and AR can be relatively costly and is often used only as a supplementary approach to enhance understanding and accurate planning before actual construction.

Progress monitoring is an essential component of project management, involving the collection, analysis, recording, and reporting of project progress performance. In construction, augmented reality (AR) has shown great promise as a tool for progress tracking and monitoring. Typically, an AR-based progress monitoring system involves collecting site data through means such as photogrammetry and laser scanning, organizing the as-built data, and comparing it with as-planned data provided by model software like BIM or 4D-CAD. The results of the comparison are then presented visually in an AR environment, with different colors indicating whether the project is ahead of, on, or behind schedule. While AR has been found to be more effective in progress monitoring than traditional tools like Gantt charts and 2D/3D models, collecting accurate as-built data for complex projects is still challenging, and developing a robust algorithm to quantify the discrepancies between as-designed and as-built status is necessary.

AR and virtual reality (VR) offer an interactive approach to off-site training, addressing the lack of hands-on learning opportunities traditionally associated with off-site training. Through the integration of BIM and VR, learners can experience real-life scenarios, such as emergency evacuations, to improve their understanding of the construction process and their skills. Moreover, AR can merge informational activity with direct work activity to make information access more efficient. For instance, using AR to facilitate pipe assembly has yielded shorter task completion times and fewer assembly errors than the traditional approach. AR has also been explored to facilitate excavation, construction defect management, inspection, and other construction-related activities.

Coordination among project participants is crucial for successful project management. VR and AR are effective platforms for improving coordination, providing project participants with a visual understanding of their roles in the project process, and presenting project information in an interactive manner. VR and AR can enhance mutual understanding, interaction, and communication among project participants, leading to effective project planning, such as material procurement. To improve coordination through VR/AR tools, more project information must be integrated into the BIM system, and participants must embrace new technologies and modify their organizational structure and work mode to adopt new technologies.

- Existing challenges and risks

Although VR and AR have been explored extensively in the construction industry, they are still in the initial stages of application and face various obstacles and challenges that offer some directions for future work. These challenges can be classified into two parts: management and technical challenges.

For management challenges, conservatism within the construction industry is a key barrier, making it difficult to enforce the adoption of new technologies. Additionally, due to the uniqueness of construction projects, VR/AR applications (e.g., equipment investment and construction simulation) may result in high costs and time consumption, conflicting with project objectives. Few studies focus on potential management challenges of VR/AR applications, indicating that they are potential directions for future work.

For technical challenges, various technical problems need to be addressed for improving the applications of VR/AR. For VR, its main shortcomings are a limited immersive effect and expensive device requirements, inadequate sensory feedback (i.e., mainly visual, less auditory, haptic, and other senses), and lack of user comfort (i.e., motion sickness, difficulties in body movement for desktop VR). Mobile AR is the main application field for AR, and key challenges include visual occlusion, accurate location, mobility, and ergonomics requirements, and robust image registration for uncontrolled outdoor conditions, filtering ambient noise and data interferences, and adding more interactivity features to the AR. (Fu & Liu, 2018)

Table 1. Existing risks and solutions in construction management and scheduling

Construction schedule risks	Solutions from VR/AR
Design quality	Decreasing design errors by assisting designer; Facilitating collaborative design and design review; Improving owners' and end-users' involvement in design.
Design change	Facilitating design review; Improving owners' and end-users' involvement in design.
Design delay	Facilitating collaborative design and design review; Speeding up owners' decision.
Decision efficiency	Improving owners' involvement; Improving coordination among project participants.
Inaccurate time estimation	Improving the quality of planning and schedule by virtual construction or VR prototype.
Error in execution	Simulating construction process before actual construction; Staff training (virtual, interactive and collaborative training); Assisting construction operation on site.
Dispute	Improving coordination among project participants.
Poor management and supervision	Progress monitoring; Improving coordination among project participants.
Material and equipment productivity	Automated material and equipment flow tracking; Improving coordination among participants.
Qualified labor	Staff training (virtual, interactive and collaborative training).
Labor productivity	Staff training (virtual, interactive and collaborative training); Assisting construction operation on site.

4.5.2 Optimizing Steel Construction Processes with RFID and Real-Time VR Simulation

This research explores the use of Radio Frequency Identification (RFID) and VR simulations in construction projects to improve control and optimization. The team implemented a Building Information Model (BIM) model in a VR environment to analyze construction processes. The architect, engineer, and contractor team can gain interactive operation, simulation, and optimization experiences by developing and critiquing construction sequences in the virtual environment. The real-time VR simulation with RFID and BIM database integration improves construction data collection and enables exploration of different construction sequences.

This paper highlights the limitations of traditional tools such as robots, webcams, and monitors in capturing site changes and updating VR systems in real-time and in detail in construction processes. It proposes the use of RFID/BIM enriched VR environments as a solution to this problem. The research aims to achieve information visualization and user-computer interaction in steel structure projects by displaying a BIM model in a VR environment and using web-based RFID to obtain real-time component data from the actual steel fabrication and erection sequence. The study also explores how the combination of RFID, BIM, and VR can reduce errors in steel fabrication and erection and assist in decision-making to optimize the erection sequence in steel construction.

- Building Information Model (BIM)

Building Information Modeling (BIM) is a model-based technology that uses a database of project information, providing a 3D view of the construction project and allowing for the documentation of the entire building life cycle. BIM can substantially reduce lead times, make the construction process more flexible and less wasteful, and perform energy analysis. However, there are still some drawbacks to BIM, including little compatibility and limited data management ability, which need to be improved. The implementation of RFID tagging technology could enhance the quality, completeness, and currency of building information models, leading to industry-wide changes in business practice.

- Radio Frequency Identification (RFID)

RFID technology has advantages over traditional barcode systems for identifying steel assets because RFID tags do not require human involvement in scanning, and they can be integrated into design systems. RFID technology has been implemented in the construction industry for asset visibility, control, and tracking. Active RFID technology can be used for order fulfillment in leasing operations, personnel tracking, and access control. RFID technology can also bring the construction industry closer to the goal of up-to-date life cycle building information models at minimal cost, providing equal accessibility to everyone and future innovation. Using RFID tags, steel parts can be distinguished with a hand-held scanner, enabling real-time updates of project information. This research suggests that RFID tags should be used for steel structure fabrication and erection.

- Virtual Reality (VR) simulation in steel construction

The use of Virtual Reality (VR) simulation in steel construction offers a valuable tool for visualizing construction projects and solving problems during the virtual construction process. By defining a 3D VR model as a set of individual steel components, the simulation allows for the piece-by-piece construction process to be visualized on a computer screen or in an immersive virtual environment. The 3D model can be created using BIM software and converted to VRML using Autodesk® VIZ®. The proposed BIM/RFID VR system utilizes Industry Foundation Classes (IFC) to define the data model of the BIM system, providing a non-proprietary and globally available format for describing the behavior, relationship, and identity of a component object within a model.

- RFID-Enabled BIM Framework for Improved Decision Making in Steel Construction

The implementation of RFID in BIM models for steel construction aims to address the uncertain conditions and risks on a construction site by utilizing a BIM/RFID VR framework supported by three main components: Manufacture Information System (MIS), Web-Base BIM Control System (WBCS), and Decision Support System (DSS). The proposed system integrates on-line analytical processing, real-time jobsite control system, and decision tree and other decision support software. The bottom layer includes building code and safety regulations, BIM 3D files, Project Scheduling Files, Web-based PDA communication techniques, and GPS, RFID, and other identification techniques. The system generates a result that has great potential for saving construction time, decreasing cost, improving the project safety record, or achieving better quality at the end of the construction process.

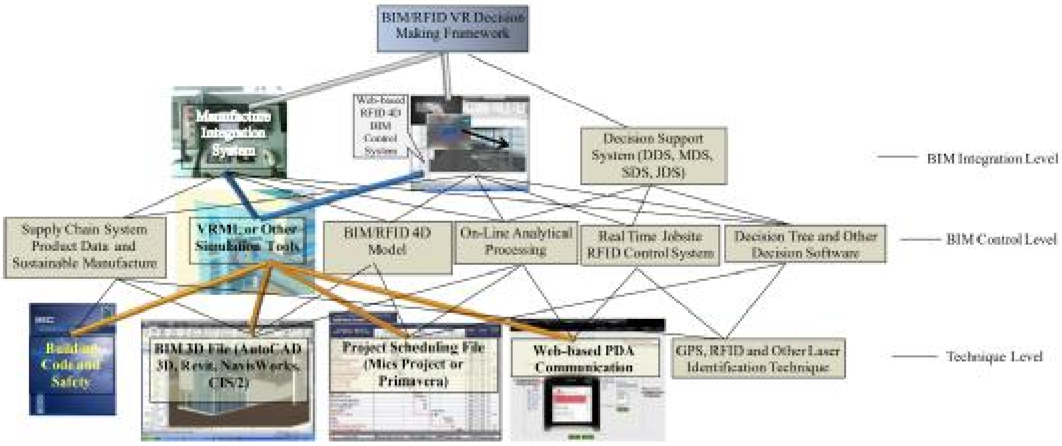

Fig. 35: BIM/RFID VR framework components and relationship

- The Case study

This paper describes a case study in which a user uses RFID technology to trace the members of a steel connection in a construction project. When the user encounters a problem with the connection, they use the BIM/RFID Framework to find three options to solve the problem, and the Project Manager decides to use option 2, which involves welding another shear plate on the same side as the incorrectly installed one. The paper also introduces the concept of a Data Hub, which is used to manage the data in the BIM/RFID VR framework's database. The Data Hub includes a data access and data delivery interface, an ETL service layer, and applications such as a real-time jobsite control system and decision software. The benefits of using the Data Hub service engine include synchronization and reconciliation of conflicting data changes, enforcing semantic consistency of the information, and generating unique persistent identifiers. The purpose of the Data Hub design is to build a complete transactional environment that maintains its data integrity.

This case study describes the optimization of steel fabrication and erection processes for Nice Quality Steel (NQS) Company using a proposed BIM/RFID framework. NQS uses various software, such as AutoCAD, SDS/2, MS Project, and MS Excel, in their design, fabrication, and project scheduling processes. They also have a CNC automated fabrication system and use different shipping methods for their products.

The proposed BIM/RFID framework helps in decision-making by listing all resolvable questions under a search menu, which users can navigate through and answer in dialog boxes. The framework can also coordinate with NQS's CNC system by using the RFID system to label steel components and assign information to RFID tags. The BIM team creates 3D format Revit and Navisworks files, uses SDS/2 and Navisworks for the design support system, and the scheduling and planning job uses BDM to find an optimal plan. Overall, BIM can bring more benefits to NQS workers and projects by optimizing their fabrication and erection processes.

The BIM/RFID Framework is a technology-driven system that allows for optimal scheduling, planning, and management of steel erection projects. Compared to traditional methods, BIM/RFID provides real-time jobsite feedback, adjusts schedules quickly, and disseminates schedules via the internet. By inputting RFID into a BIM model and using simulation and matrix calculations, an optimal steel erection order can be determined, saving time, space, and cost while eliminating errors and confusion. The BIM/RFID Framework brings three major benefits to the AEC industry: timesaving for scheduling and planning, minimizing steel storage space, and smart IE management technologies. With the help of RFID technology, the 4D BIM/RFID Framework can easily control the erection sequence by pieces, and the erection plan can follow the RFID marked 4D BIM/RFID model.

- Conclusion:

The proposed model that combines Building Information Modeling (BIM), Radio Frequency Identification (RFID), and Virtual Reality (VR) Simulation is a promising tool for the steel fabrication and site steel erection process. It allows for real-time steel erection monitoring, planning jobs, verifying erection information, controlling job sequence, site inspection, and other field-related jobs. It can also help AEC professionals make decisions by using the erection progress shown on the BIM control and testing system.

- Limitations:

The BIM/RFID VR Framework faces two main limitations. Firstly, the concern for data safety has limited the development of BIM in the construction industry. Subcontractors are legally using BIM resources and reading project information from the same BIM environment and systems. This brings a problem for data safety and user limitations. Secondly, BIM tools marketed by different companies, designers, programmers, and software developers may have conflicts, leading to concerns about data reliability. (Xie, Shi, & R.A. Issa, 2011)

5. FINDINGS AND DISCUSSION

5.1 Summary of research results

Case Study Title: Heavy Mobile Crane Planning for Modular Construction

Objectives:

- To improve the planning and control of heavy mobile cranes in modular construction.
- To reduce costs and speed up the construction process.

Methodology:

- Development of a virtual reality (VR) simulator, VrCrane, for heavy mobile cranes.
- Followed five main steps, including creating a 3D model of the construction site and the selected crane, and allowing users to control every possible degree of freedom of the mobile crane.
- Used Building Information Modeling (BIM) models.

Results:

- VrCrane provided users with a realistic experience of the lifting operation.
- Improved collaboration between operators, planners, and engineers.
- Real-time calculations and information presentations increased common understanding and facilitated communication among decision makers and key stakeholders.

Implications:

- VR technology can provide useful extra information and improve collaboration in the architecture engineering and construction (AEC) industry.
- Proper use of heavy mobile cranes can reduce costs and speed up the construction process.

Limitations:

- High-performance computer and virtual reality equipment are necessary for effective operation of the simulator.
- Dynamic changes in the construction site and external factors such as weather conditions are not accounted for in the simulator.
- Trained personnel are required to operate the simulator, which may be a limitation in certain settings.

Case Study Title: Implementation of Virtual Design and Construction: A Case Study in an Egyptian Construction Company

Objectives:

- To explore the potential of virtual reality (VR) in construction through the implementation of Virtual Design and Construction (VDC) in an Egyptian construction company.
- To evaluate the impact of VDC implementation on various project objectives in the construction industry.
- To identify limitations and challenges of implementing VDC in the construction industry.

Methodology:

- The study utilized a case study approach and implemented three applications of VDC, including VR 4D simulation and tracking, clash analysis and VR design review, and VR real-time collaboration, in an office building project in an Egyptian construction company.
- A survey was conducted among industry professionals to evaluate the impact of VR implementation in construction through VDC.

Results:

- The implementation of VDC in the office building project using the three applications showed potential benefits, such as efficient progress tracking, early detection of design conflicts and construction challenges, and potential cost and time savings.
- The survey results showed that VR implementation through VDC has a high to very high impact on various project objectives, including identifying design issues and clashes, reviewing designs pre-construction, improving coordination, and ensuring client satisfaction.
- Employers, contractors, and consultants provided positive feedback on VR implementation, indicating a possible transition from traditional building information modeling (BIM) workflows to VDC workflows in the future.

Implications:

- VDC implementation can have a significant impact on various project objectives in the construction industry, leading to potential cost and time savings.
- VR technology can aid in identifying design conflicts and construction challenges early on, improving coordination, and ensuring client satisfaction.
- Employers, contractors, and consultants may consider transitioning from traditional BIM workflows to VDC workflows in the future.

Limitations:

- A lack of technology background and awareness may hinder the implementation of VDC in the construction industry.
- Resistance to change may also pose a challenge to the adoption of VDC in the construction industry.
- High initial implementation costs may be a limiting factor for some construction companies.

Case Study Title: A case study of Virtual Reality and Environmental Sustainability in the Automotive Industry

Objectives:

- To explore the feasibility of using virtual reality (VR) technology in manufacturing to reduce environmental impact.
- To demonstrate the advantages of adopting a multi-user VR system in interaction design.
- To identify the potential areas of VR application contributing to environmental sustainability in the automotive industry.

Methodology:

- Developed and tested a VR demo in an automotive company with research and development centers in Sweden and manufacturing plants in China.
- Used 3D laser scanning technology to capture input data and Unity3D as the development platform to integrate different data sources.
- Tested the VR demo in multiple phases, including a pilot test with colleagues from Gothenburg in Sweden and Gaithersburg in the United States, a second test in Sweden with external participants, and a final test in the case company in Gothenburg with 14 participants from different departments.
- Collected feedback through a scale-rating survey and 15 interviews to identify the potential areas for VR implementation in the case company.
- Conducted a focus group discussion with the engineering department to discuss the biggest potential of VR application contributing to environmental sustainability.
- Designed a questionnaire for verification to collect feedback from a broader scope of users.

Results:

- The VR demo was able to reduce travel frequencies for design review, thus contributing to environmental sustainability.
- 17 potential areas of VR application were identified within three main areas: Analysis, Communication, and Visualization.
- The identified areas of VR application could be done with standard VR equipment that is available today at the case company, while some require planning and will be in place within a year.
- The study also revealed the potential for VR to address the needs for long-distance communication and collaboration by providing a more immersive and interactive experience.

Implications:

- The use of VR technology for design reviews can contribute to environmental sustainability in the manufacturing industry by reducing travel frequencies.
- VR technology can be applied to various areas in manufacturing, such as analyzing ergonomic issues, enabling better communication, and visualizing matters and issues to enhance understanding.
- VR technology can address the needs for long-distance communication and collaboration, which can reduce the need for business trips and contribute to environmental sustainability.

Limitations:

- The case study only focused on one company in the automotive industry, and the results may not be applicable to other industries.
- The study only identified the potential areas of VR application, and further research is needed to investigate the effectiveness of using VR technology in those areas.
- The study did not consider the cost and feasibility of implementing VR technology in manufacturing, which may be a limitation for smaller companies.

Case Study Title: An Experimental Study in the Built Environment Domain

Objectives:

- To investigate the relationship between 3D perception and presence in virtual environments.
- To contribute to the understanding of the factors that promote presence in virtual environments.
- To provide directions for developing and implementing more effective VR systems.

Methodology:

- A controlled within-group experiment with a within-subject design.
- Perception and presence questionnaires were used to test the hypothesis in two different virtual environments (non-immersive and immersive).
- Low-fidelity Building Information Modelling (BIM) models were used in both VR modes to focus on technical specifications.
- Participants' 3D perception responses were standardized in the VR conditions against their responses in the physical environment to observe the effects of display mode, stereopsis, field of view, and interactivity on 3D perception and presence.
- Identical low-fidelity graphics/rendering effects and user interfaces were used in both VR modes.
- The non-immersive VR mode used a high-performance laptop, keyboard, and mouse for interaction devices.

Results:

- The results indicate that incorporating advanced depth representation and visualization techniques may not necessarily contribute to highly immersive experiences.
- Developers can focus on addressing other factors to promote engagement and presence, such as intuitive interaction methods.

Implications:

- The study provides important implications for VR applications in the architecture, engineering, construction, operation, and facility management sector.

- The findings suggest that non-stereoscopic VR systems can still provide high levels of presence if other presence-promoting factors are included.
- Developers can focus on developing VR systems that prioritize intuitive interaction methods to promote engagement and presence.

Limitations:

- The study utilized a low-fidelity BIM model, which may not fully represent real-world scenarios.
- The study only tested two virtual environments and did not consider other factors that may influence 3D perception and presence.

Case Study Title: The Role of Urban Participation in the Field of Urban Design Using Virtual Reality

Objectives:

- To test the effectiveness of virtual reality tools in promoting public participation in urban design
- To assess the ease of use, cost-effectiveness, efficiency, and satisfaction of the virtual reality tool among participants
- To evaluate the potential of virtual reality tools in areas with limited access to physical participation

Methodology:

- Conducted a study in Beit Hanoun, Gaza, Palestine in January 2017
- Tested the virtual reality tool with 30 citizens and decision-makers, 25 of whom responded.
- Participants downloaded interactive virtual reality files containing two models for viewing proposals.
- Used an electronic questionnaire divided into four parts to obtain feedback from participants.
- Evaluated the tool based on criteria such as ease of use, cost of entry, efficiency, interactivity, ease of communication, and satisfaction.

Results:

- The high-interactive view of the virtual reality tool was easier to use and had a good level of completion for scientific participation.
- The cost of implementing and processing the tool was virtually nonexistent.
- The tool was efficient in attracting citizens and achieving its objectives.
- The evaluation criteria provided a comprehensive understanding of the tool's performance, and the results showed that it was well received by participants.

Implications:

- The virtual reality tool showed promise in promoting public participation in urban design.

- The tool was easy to use, cost-effective, and efficient in achieving its objectives.
- The findings may be relevant for future research in the field of virtual reality and public participation, particularly in areas with limited access to physical participation.

Limitations:

- The study was conducted in a specific location and may not be applicable to other contexts..
- The sample size was relatively small, which may limit the generalizability of the findings.
- The study only tested the tool with one type of project, and further research is needed to assess its effectiveness in different types of urban design projects.

Case Study Title: Development and Evaluation of a Virtual Reality Safety Training Application for Roofing Professionals

Objectives:

- To assess the feasibility of using VR technology for safety training in the roofing industry
- To develop a VR safety training program specifically for roofing professionals
- To capture the industry's perception of VR training for safety

Methodology:

- Progressive elaboration approach with industry inputs to develop and validate different scenarios.
- Ten sections designed to cover various ladder-related tasks, each assuming a new roofing worker who needs to evaluate safety risks.
- VR application optimized for Oculus Quest 2 headset and developed using Unity game engine.
- Industry experts involved in testing each section of the VR application to ensure correctness and applicability.
- A task force formed with the primary professional organization for roofing contractors in the US for quality control throughout design and development phases, in addition to internal review process.
- Beta version of the application tested by industry task force members and their employees who provided feedback via a survey.
- Survey used Likert scale to measure agreement levels of users and collected responses for 10-day period.
- 46 valid samples used in analysis, and survey's internal consistency rated as very good with Cronbach's alpha of 0.80 and 0.89 for impacting factors and VR feature sections, respectively.

Results:

- Exposure to VR safety training positively impacts industry practitioners, especially younger generations.
- VR safety training module specifically for roofing sector is more applicable to their routines than general safety training.
- Survey responses indicate high agreement levels with the VR training module and its features.

Implications:

- VR technology is a feasible and effective tool for safety training in the roofing industry.
- VR safety training programs can be tailored to specific sectors, making them more applicable to their routines and needs.
- Industry involvement and collaboration are crucial for quality control and ensuring applicability of VR safety training programs.

Limitations:

- Small sample size of 46 valid samples
- Limited to the roofing industry and ladder-related tasks
- Survey responses may be subject to bias or social desirability effects

Case Study Title: Mitigating Costly Errors: The High Stakes of Tolerances in Hyperscale Data Center Construction

Objectives:

- To address the issue of costly errors in hyperscale data center construction due to tolerance deviations
- To implement ARQ workflows and Atom technology to streamline inspections and enhance communication.
- To proactively identify and address issues to minimize the need for rework and prevent additional costs and delays.

Methodology:

- Deployed the Atom, an engineering grade AR headset, on site to facilitate coordination and construction.
- Implemented ARQ workflows that linked with Autodesk's BIM 360 software for real-time validation in the field.
- Stationed an XYZ Field Application Engineer on site to ensure accuracy of inspections and analysis of findings.
- Conducted inspections throughout the project, from advanced coordination to construction and beyond.

Results:

- Doubled the number of inspections conducted on the project.

- Proactively identified and addressed 489 early issues using the Atom technology, thereby preventing additional costs and delays.
- Ensured accuracy of inspections and analysis of subsequent findings through the stationing of an XYZ Field Application Engineer on site.
- Enhanced project-wide communication and minimized the need for rework.

Implications:

- AR technology can significantly improve inspection accuracy and streamline construction processes.
- Real-time validation in the field can prevent costly errors and delays.
- Stationing an expert on site can ensure the accuracy of inspections and analysis of findings.

Limitations:

- The study was conducted on a single hyperscale data center project, and further research is needed to determine the effectiveness of the approach in other projects and industries.

Case Study Title: Identifying Mechanical Equipment Setting-Out Errors with Augmented Reality

Objectives:

- To identify potential errors during the installation of mechanical and electrical equipment in a pharmaceutical plant construction project in Ireland
- To prevent delays, disruptions, and rework costs caused by errors during equipment installation.

Methodology:

- The Atom was deployed by the main contractor's mechanical package manager to inspect a key HVAC location.
- The inspection was used to assess the installation of air handling units (AHUs) and dehumidifiers to ensure they were in the correct location and didn't clash with upcoming interfacing ductwork.
- The installers used 2D drawings to set out and position the two dehumidifiers in the area, but the drawings did not contain all the relevant information.
- The Atom's Augmented Reality technology helped identify an error in the orientation of the dehumidifiers, preventing critical lifting equipment from being removed and interfacing works from being installed incorrectly.
- The error was rectified quickly and efficiently, saving valuable time on the schedule and rework costs from the budget.

Results:

- The use of Augmented Reality technology helped identify a setting-out error in the installation of dehumidifiers.
- The error was identified and corrected before critical lifting equipment was removed and interfacing works were installed incorrectly.

- The inspection not only ensured that the dehumidifiers were installed correctly, but it also prevented potential delays and disruptions to the entire project.
- The Augmented Reality Headset's ability to detect errors in real-time helped to ensure that the project was completed on time and within budget.

Implications:

- The use of Augmented Reality technology can help prevent errors during the installation of complex mechanical and electrical equipment.
- Real-time detection of errors can save valuable time and resources, preventing delays and disruptions to the project.
- Augmented Reality technology can improve project coordination and communication between contractors and project managers.

Limitations:

- The use of Augmented Reality technology may require additional training for construction workers and project managers.
- The cost of implementing Augmented Reality technology may be prohibitive for some construction projects.
- The technology may not be effective in all situations, and traditional methods may still be necessary in some cases.

Case Study Title: The Application of VR and AR in Construction Schedule Control

Objectives:

- To explore how VR and AR can help contractors manage construction schedules, ultimately leading to improved project outcomes.

Methodology:

- A review of existing literature on the benefits of VR and AR in construction schedule control.

Results:

- VR and AR contribute to schedule control through planning and scheduling, progress monitoring, improving labor productivity, and improving coordination among participants. They provide a better simulation approach to construction planning and scheduling by visualizing construction plans and can be used to find the best construction scenario under condition constraints. AR is effective in progress monitoring and comparing as-built data with as-planned data provided by model software. VR and AR offer an interactive approach to off-site training, providing learners with real-life scenarios to improve their understanding and skills.

Implications:

- VR and AR offer significant benefits in construction schedule control, leading to improved project outcomes.

Limitations:

- Simulation using VR and AR can be relatively costly and collecting accurate as-built data for complex projects is still challenging.

5.2 Challenges from the use of VR

Virtual reality (VR) has gained popularity in various fields, including design and construction. However, its use also presents several challenges, including limitations in the sketching or design process. Participants may not be able to exploit the full potential of VR due to the increased cognitive load. In addition, unfamiliarity with the technology, reliance on a technician for navigating the environment, and physiological challenges such as dizziness and discomfort with HMDs.

Apart from these challenges, other issues also arise, such as limitations in the number of users and the rendering quality, as well as the time-consuming setup of the HMD system. Moreover, the need for stronger pedagogic anchoring to ensure that the excitement over the technology does not overshadow the focus on learning.

Psychological discomfort was also reported to be a challenge, as participants felt uncomfortable using the technology in front of others, which could occlude their own vision. These challenges need to be addressed to enable the full potential of VR to be realized in the design and construction industry. (STRAND, 2020)

- Visualization challenges:

There are several factors to consider when displaying immersive visuals. Combining software and hardware components is necessary to achieve 3D imagery for exploration. The desktop display usage is the basic technology that uses a central processing unit (CPU) within a computer to output immersive visuals to the monitor screen (LCD or LED) or the standard screen projection from a projector. The desktop display has some advantages, but it lacks mobility and realism due to the display structures. Another approach to immersive visuals projection is the use of a VR Cave system, which can have different designs of setups and outputs of immersive visuals. HMD is another wearable technology that can come with different device specifications placed on the user's head for tracking and visualization purposes. HMD can enhance users' sense of presence while exploring inside VE, but it may cause users to experience motion sickness due to the visualization features that it delivers. Visual coordination is also an issue when devices are shared among users during usage.

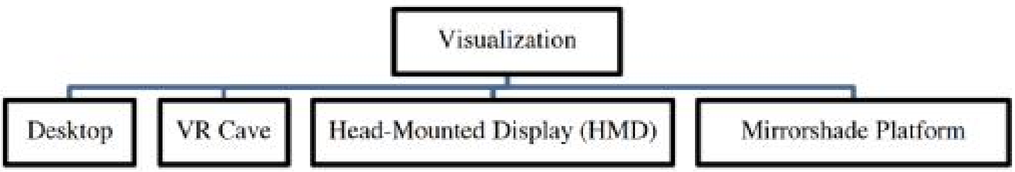

Fig. 36: Virtual Reality visualization approach

- Navigation challenges:

The objective of the VR navigation system is to meet the high level of immersion during users' experiences. The system needs a basic constructed 3D VE, controller device for users to input, tracking, and visualization device before users can perform navigation within it. However, there is still a gap in achieving physical acceptance similar to the touch screen navigation. Space issues from research noted the constraint on safety and restricted area to perform movement. Furthermore, there are limitations on the number of users allowed to be in the area of the application system during the exploration activity. The authors also emphasized the discomfort of cabled HMD used in the early version.

- Interaction challenges:

The interaction design of a VR system is crucial for creating a sense of presence and engagement among users during exploration activities. The system's output should allow users to interact with the virtual environment in a natural and intuitive manner, like real-world interactions. However, achieving this goal can be challenging due to the limitations of current input devices and the complexity of creating responsive and believable virtual objects and environments.

One common approach to interaction design is through the use of handheld controllers, such as gamepads, motion controllers, and haptic feedback devices. These devices provide a physical means for users to interact with the virtual world, but they can also be limiting in terms of accuracy, responsiveness, and user comfort. For example, handheld controllers may not provide sufficient tactile feedback or may require a steep learning curve for users to become proficient. Another approach to interaction design is through the use of natural user interfaces (NUIs), which aim to provide more intuitive and natural ways for users to interact with the virtual environment. Examples of NUIs include voice recognition, gesture recognition, and eye tracking, among others. NUIs have the potential to create more immersive and engaging experiences, but they also require more advanced hardware and software, which can be costly and difficult to implement.

Other challenges in interaction design include creating believable and responsive virtual objects, designing effective feedback mechanisms, and ensuring that the system is accessible and user-friendly for a wide range of users. As VR technology continues to evolve, it is likely that new interaction paradigms and techniques will emerge, creating new opportunities and challenges for VR designers and developers. (Chong, Lim, & Tan, 2016)

6. CONCLUSION

6.1 Summary of main findings

The case studies cover a wide range of topics related to the use of advanced technologies in the construction industry. The implementation of augmented reality and virtual reality has become a promising solution for reducing errors and improving safety in construction projects. The case study "Identifying Mechanical Equipment Setting-Out Errors with Augmented Reality" demonstrated the effectiveness of using augmented reality in identifying errors during installation, which resulted in significant time and cost savings. Similarly, "Mitigating Costly Errors: The High Stakes of Tolerances in Hyperscale Data Center Construction" emphasized the importance of accurate tolerances in the construction of data centers to avoid costly rework.

The case study "Development and Evaluation of a Virtual Reality Safety Training Application for Roofing Professionals" highlighted the potential of virtual reality in providing safety training for construction workers. In addition, the use of virtual reality in urban design, as demonstrated in "The Role of Urban Participation in the Field of Urban Design Using Virtual Reality," can enhance community participation and engagement in the design process.

The case study "A case study of Virtual Reality and Environmental Sustainability in the Automotive Industry" showed the potential of virtual reality in promoting environmental sustainability in the manufacturing process. The implementation of virtual design and construction, as shown in "Implementation of Virtual Design and Construction: A Case Study in an Egyptian Construction Company," can improve communication and collaboration among stakeholders, resulting in better project outcomes.

Finally, the case study "Heavy Mobile Crane Planning for Modular Construction" demonstrated the use of simulation and modeling to optimize crane planning in modular construction projects. Overall, the case studies showed that the use of advanced technologies such as augmented reality, virtual reality, and simulation can result in significant improvements in safety, efficiency, and sustainability in the construction industry.

In conclusion, the case studies highlighted the potential of advanced technologies in improving various aspects of the construction industry. However, their successful implementation requires careful planning, collaboration, and training. Therefore, companies in the construction industry should invest in the adoption of these technologies and provide adequate training to their employees.

6.2 Recommendations for future research

Based on the analysis of the case studies, the following recommendations for future research can be made:

- Further research should be conducted on the effectiveness of using augmented reality (AR) and virtual reality (VR) technologies in construction projects. This can include evaluating the impact of AR and VR on reducing errors, improving efficiency, and enhancing communication between stakeholders.

- There is a need for research on the development of AR and VR safety training applications for other industries. The roofing industry case study demonstrated the potential of AR and VR in enhancing safety training, and this can be extended to other high-risk industries.
- Future research should explore the potential of AR and VR in facilitating stakeholder engagement in the urban design process. The case study on the role of urban participation using virtual reality showed that these technologies can enhance stakeholder participation and improve the decision-making process.
- There is a need for further research on the integration of AR and VR technologies in the automotive industry for environmental sustainability purposes. The case study on virtual reality and environmental sustainability in the automotive industry highlighted the potential of these technologies in reducing environmental impact.
- Research is needed to evaluate the implementation of virtual design and construction (VDC) in other construction companies and contexts. The case study on the implementation of VDC in an Egyptian construction company demonstrated the benefits of VDC in improving project delivery and reducing errors.
- Finally, there is a need for further research on the planning of heavy mobile cranes for modular construction. The case study on heavy mobile crane planning for modular construction demonstrated the potential of simulation tools in optimizing crane planning and improving project efficiency.

References

Lovreglio , R., Gonzalez, V., Feng, Z., Amor, R., Spearpoint , M., Thomas, J., . . . Sacks, R. (2018). Prototyping virtual reality serious games for building earthquake preparedness: The Auckland City Hospital case study. Advanced Engineering Informatics.

S. Bakhoum, E., A. Younis, A., K. Aboulata, H., & R. Bekhit, A. (2023). Impact assessment of implementing virtual reality in the Egyptian construction industry. Ain Shams Engineering Journal.

STRAND, I. (2020). Virtual Reality in Design Processes. form ACADEMIC.

The Benefits of Using Augmented Reality in Construction. (n.d.). Retrieved from XYZ Reality: https://www.xyzreality.com/resources/9-x-roi

Virtual and Augmented Reality ,Finding real opportunities in virtual worlds. (n.d.). Retrieved from CCS Insight: http://www.ccsinsight.com/research-areas/virtual-and-augmented-reality/

XYZ Reality. (n.d.). Retrieved from Mechanical Equipment Setting-Out Error: https://www.xyzreality.com/resources/mechanical-equipment-setting-out-error

A guide for virtual and Mixed Reality for Industrial Design. (n.d.). Varjo Technologies.

Alizadehsalehi, S., Hadavi, A., & Huang, J. C. (2019). Virtual Reality for Design and Construction Education Environment . AEI.

Augmented Reality for Construction. (2023). Retrieved from XYZ Reality: https://www.xyzreality.com/augmented-reality-for-construction

Case Kia: Global design reviews can go from days to an hourr . (n.d.). Retrieved from https://varjo.com/case-kia-autodesk-vred-driving-the-future-with-xr-collaboration-in-car

Chong, H., Lim, C., & Tan, K. (2016). Challenges in Virtual Reality System: A Review. AIP.

Fares, F., Taha, D. S., & Sayad, Z. T. (2018). Achieving public participation in inaccessible areas using virtual reality a case study of Beit Hanoun – Gaza – Palestine. Alexandria Engineering Journal.

Fu, M., & Liu, R. (2018). The Application of Virtual Reality and Augmented Reality in Dealing with Project Schedule Risks . Construction Research Congress .

Ghobadi, M., & Sepasgozar, S. M. (2020). An Investigation of Virtual Reality Technology Adoption in the Construction Industry. In Smart Cities and Construction Technologies. IntechOpen.

Halder, S., Afsari, K., Serdakowski, J., DeVito, S., & Ensafi, M. (2022). Real-Time and Remote Construction Progress Monitoring with. Buildings.

History of virtual reality. (n.d.). Retrieved from TheFrankly Institute: http://www.fi.edu/en/virtual-reality/history-of-virtual-reality

HTC Vive. (2022). Retrieved from HTC: https://www.vive.com/us/

Kayhani, N., Taghaddos, H., Noghabaee, M., & Hermann, U. R. (2018). Utilization of Virtual Reality Visualizations on Heavy Mobile Crane Planning for Modular Construction. 35th International Symposium on Automation and Robotics in Construction.

Oculus Quest. (2022). Retrieved from Oculus: https://www.oculus.com/quest/

odu, X., Gong, L., Berce, A., Johansson, B., & Despeisse, M. (2021). Implications of Virtual Reality on Environmental Sustainability in Manufacturing Industry: A Case Study. 54th CIRP Conference on Manufacturing Systems.

Orihuela, P., Pacheco, S., Orihuela, J., Yaya, C., & Aguilar, R. (2019). Application of Virtual . Proc. 27th Annual Conference of the International. Group for Lean Construction (IGLC). Dublin.

Paes, D., Irizarry, J., Billinghurst, M., & Pujoni, D. (2023). Investigating the relationship between three-dimensional perception and presence in virtual reality-reconstructed architecture. Applied Ergonomics.

Rokooei, S., Shojaei, A., Alvanchi, A., Azad, R., & Didehvar, N. (2023). Virtual reality application for construction safety training . Safety Science .

Wang, S.-K., & Chen, H.-M. (2020). A Construction Progress On-site Monitoring and Presentation System Based on The Integration of Augmented Reality and BIM. 37th International Symposium on Automation and Robotics in Construction .

Wu, J. (2018). A Space Design Teaching Model Using Virtual Simulation Technology. International Journal of Emerging Technologies in Learning (iJET).

Xie, H., Shi, W., & R.A. Issa, R. (2011). Using rfid and real-time virtual reality simulation for optimization in steel construction.

XYZ Reality. (2023). Retrieved from On-Site Prefabricated Inspections: https://www.xyzreality.com/resources/using-ar-to-ensure-precision-in-prefabricated-construction

XYZ Reality. (2023). Retrieved from On-Site Prefabricated Inspections: https://www.xyzreality.com/resources/on-site-prefabricated-inspections

List of figures