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Enhancing Construction Management Education through 4D BIM and VR: Insights and Recommendations

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Abstract: Traditional teaching methods in construction management education often face challenges in providing students with practical, real-world experiences crucial for skill development. To address these limitations, this study explores the potential of integrating building information modeling (BIM) and virtual reality (VR) as educational tools for construction management students. Our aim is to assess the effectiveness of a 4D-BIM-based VR simulation in enhancing student's learning experiences and performance in construction project management. This research employs a mixed-method approach, combining quantitative data and qualitative insights from a comparative experiment involving undergraduate students. Quantitative data were collected through objective error detection measures in construction sequences and processes, while qualitative insights were gathered from participant feedback. The findings highlight that students using VR-based simulations detected more errors in construction sequences and processes than in traditional 2D drawings, showcasing the utility of BIM and VR-enabled approaches in teaching construction management. This study contributes to the ongoing discourse on integrating advanced technologies into educational practices, particularly in construction management, where practical hands-on experiences are crucial for skill development and real-world application.

Keywords: BIM; VR; immersive environments; project planning; construction management education

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1. Introduction

The construction industry plays a vital role in the world economy; the complicated nature of this industry needs a high level of education and deep experience to cope with the challenging requirements [1]. Recent technological advancements have transformed construction education significantly, fostering collaboration and prompting the adoption of diverse teaching methodologies [2–4]. Building information modeling (BIM) has emerged as an indispensable tool that adds value to facilitate design and construction communication and visualization [5]. Virtual reality (VR) integration with BIM defines the project data in new visualized representations, allowing for better collaboration, information delivery, and student cognizance [6,7]. Providing these assistive tools for construction management students further supports their knowledge acquisition and educational experience [8].

Traditionally, teaching construction management courses relies on outdated methods such as 2D drawings, schedules, and documents, expecting students to understand and link activities that differ in timing and nature of project planning, including developing project activity sequencing, schedules, safety plans, resource estimates, etc. Project management involves overseeing the planning, execution, and monitoring of construction projects to ensure they are completed within scope, time, and budget constraints. Cost estimation focuses on predicting the expenses of construction projects, involving detailed assessments of materials, labor, equipment, and overhead costs. Scheduling entails creating timelines and sequencing tasks to ensure project milestones are met efficiently. Quality control emphasizes maintaining project standards and specifications through inspections and quality assurance. Safety protocols are critical in ensuring construction sites adhere to safety regulations to prevent accidents and injuries. However, this approach assumes that students will actively engage, analyze, review, and manage projects across different levels and dimensions, which can be overly complex and challenging for learners. Traditional teaching methods in construction management become even more challenging when instructors lack real-world field experience, necessitating collaborative approaches to compensate for this limitation. The fundamental challenge lies in comprehending information derived from conventional 2D project drawings and other traditional documents, necessitating a deep understanding of these representations. Although information technology and 3D visualization tools have evolved and become more reliable, the limited adoption of BIM and VR in construction management education persists due to the absence of comprehensive guidelines, references, and tailored content designed specifically to align with course objectives. [9,10].

This study explores the potential of building information modeling (BIM) and virtual reality (VR) as educational tools for construction management students. The primary aim of this paper is to acquire valuable insights into how 4D-BIM-based VR simulations can enhance the learning experience and facilitate knowledge acquisition among construction management students.

2. Literature Review

2.1. Construction Management Education

Construction management education plays a vital role in preparing professionals for the complexities of the construction industry. It encompasses a range of disciplines, including project management, cost estimation, scheduling, quality control, and safety protocols. Teaching complicated details, real-world scenarios, and construction challenges cannot be effectively achieved by traditional construction management education tools alone [11]. The intricacies of teaching construction planning and management are exacerbated by the dynamic and unpredictable nature of construction projects. Researchers have highlighted the importance of enhancing construction learning methods through site visits, as they provide students with valuable real-life experiences that significantly contribute to their understanding of the subject matter [12,13]. Additionally, incorporating new learning approaches based on active learning, such as experiential learning, games and simulations, and computer-based learning, can enhance students' engagement and learning experiences. These methods allow for more thorough learning and active participation in real-world construction activities [14,15].

Traditional techniques need to be faster, more engaging, and more efficient to be applied to large class sizes. These methods should also facilitate testing students and providing timely feedback to assess their current understanding of the concepts [14]. Researchers tried to overcome this issue by applying new and different approaches, such as integrating construction education with the industry by introducing different teaching scenarios and tools. However, Pan et al. claimed that examining the link between research-informed teaching and its diverse practice and barriers resulted in many obstacles for teachers and students to solve [16]. Furthermore, other researchers critiqued applying new technologies due to the limited amount of research on applying technologies' impact on construction teaching and learning. Additionally, there is a relatively low understanding of the processes regarding learning requirements and aspects [5].

Glick et al. suggested that students can gain more from 3D computer models that enhance complex course material with visualization [17]. Other researchers claimed that interactive environments help increase awareness regarding the different levels of complex projects by enabling interaction [14]. Messner and Horman also found that advanced communication based on visualization positively improves students' comprehension of construction planning and design reviews of complicated projects [18]. These advancements, however, lack guidance for implementation in the construction education curriculum because of the gap between research and practice [19]. Also, the disconnect between teaching and industry practice prevents the delivery of the correct information and hinders innovation practice's ability to provide reliable guidance for implementing these technologies.

2.2. BIM for Construction Management Education

Recently, BIM has exponentially grown in the architecture, construction, and engineering industry (AEC) [7]. BIM is meant to represent data in object-oriented 3D models for project data integration among all users, including planning (4D), cost (5D), facility management (6D), and sustainability (7D). Moreover, it has been cited as an effective tool for realistic visualization, coordination, collaboration, and communication among users and an excellent decision-making application for data-driven information in the AEC industry [20–22]. A recent study explored the integration of BIM into the final semester projects of undergraduate students. This investigation revealed that incorporating BIM into the educational curriculum facilitated collaborative group work and significantly improved the overall learning experiences and outcomes for both students and educators. [23]. However, despite these benefits, the practical application of BIM as a teaching tool still faces some challenges [19]. Nonetheless, BIM facilitates the utilization of virtual reality (VR) in construction education and industry. It seamlessly introduces real-world practices by enabling digital object connection and creating a physically simulated sense of presence in an enhanced immersive virtual environment (IVE), which is a digitally created space that allows users to experience and interact with a construction project in a highly realistic and immersive manner [24]. IVEs leverage BIM data to create detailed virtual representations, improving understanding and decision-making in both educational and professional contexts [25].

2.3. VR for Construction Management Education

Over the last few years, VR has been extensively implemented in construction education and training (CEET) [26]. VR simulations provide immersive experiences, effectively train individuals for hazardous situations, and offer solutions for complex problems through interactive computer-based experiences [2,6]. The perceptual experience of presence within VR contributes positively to spatial perception and comprehension. [7]. Furthermore, the VR project features preprogrammed realistic digital environments that elicit users' genuine sense of reality. This enables individuals to believe in, interact with, explore, and fully immerse themselves in the virtual experience [27]. Several researchers in construction management education have explored VR as a tool for instructional delivery, discussing its potential to enhance pedagogical approaches through gamification and assembly techniques. Anifowose et al. notably integrated gamification into their teaching approach to assist students in tackling real-world problems and discovering appropriate solutions. [28]. In addition, emphasizing the significance of hands-on training, practical experience on worksites, and problem-solving in real-world scenarios, other researchers have proposed VR as an effective guiding tool in education [9].

Numerous studies have explored the utilization of VR in construction education and training (CEET). Wang et al. (2018) critically analyzed VR-related journal papers within the CEET domain in recent years, revealing the progressive integration of VR in the AEC industry over time and highlighting its efficacy in enhancing training outcomes and improving performance [26]. Researchers have observed that greater immersion in virtual reality (VR) correlates with more significant enhancements in learning, motivation, and self-efficacy, further supporting the effectiveness of VR in improving performance [29]. On the contrary, authors recommended expanding studies on VR toolkit suitability and applicability and emerging in real education practices [26,30]. In a study by Lucas et al., surveys of students immersed in VR simulation and learning outcomes were compared with the traditional 2D teaching method to test the impact of simulation. The study highlighted the significance of incorporating VR in the education process, as students with the VR test tended to exhibit a deeper understanding of course content and improved learning outcomes [29].

2.4. BIM and VR Integration

In recent years, the integration of BIM and VR in construction education has gained substantial attention. This unique integration results in immersive visual models that significantly improve teaching methods. [27]. Educational institutions worldwide recognize the importance of incorporating BIM and VR into construction management curricula to better prepare students for the industry's evolving demands. By combining VR and BIM, students can engage in immersive learning experiences that enhance their understanding of construction principles and practices, improving their knowledge and contributing to the development of skills in areas such as design visualization, space navigation, clash visualization, hazard identification, safety training, project planning, and management [6]. The integration of BIM and VR for worksite walkthroughs has been shown to have a significant impact on both students and professionals due to its ability to provide immersive and realistic experiences, enhancing their understanding of construction processes and project management [31]. Given this context, there is compelling evidence that the integration of BIM and VR has emerged as a powerful toolset capable of enhancing understanding across various construction processes and supporting project participants in making more informed decisions [26,31].

Several studies have investigated the integration of virtual reality (VR) into construction engineering education to enhance teaching curricula [32]. Alizadehsalehi et al. used a "BIM-into-VR" model to assess BIM and VR integration based on two case studies. The authors concluded that technology implementations help improve the learning process and motivate construction students for skills development in an innovative way. Hence, VR technology has excellent potential as an educational tool [27]. A similar approach has been carried out by Hussein et al. The authors compared two different tools, VR and Xolius, as educational tools to assess their efficiency and benefits. The results underscored the importance and significance of utilizing virtual reality (VR) in education, as the immersive experience provided by VR enhanced student engagement and facilitated a better understanding of the material [33]. Lucas also surveyed construction management students using head-mounted displays in a teaching course. The study ended with positive student feedback [34]. Hence, VR can be concluded to contribute positively to the construction of academia and enhance users' cognition of complex project details.

This paper aims to advance the field through comparative analysis by developing a 4D-BIM-based VR simulation for testing undergraduate students. The research method promotes the use of immersive virtual environments (IVEs) to understand the complexities and realities of the project, bridging theoretical concepts with practical visualization [10]. BIM and VR integration in construction management education are reliable tools in many industries. The study aims to explore the potential of BIM and VR as educational tools for construction management students, with a specific focus on using 4D-BIM to enhance learning outcomes in project planning, scheduling, and error detection. This research investigates how integrating 4D-BIM with VR simulations can improve students' cognitive abilities in identifying construction sequencing errors and understanding complex project management processes.

By developing a 4D-BIM-based VR simulation specifically tailored for undergraduate construction management students, this research provides empirical evidence that demonstrates the efficacy of this integrated approach in enhancing both cognitive skills and learning outcomes. Distinct from previous studies, such as those by Alizadehsalehi et al., [27], focusing on students' general experiences with BIM and VR technology, this study introduces a novel application by integrating 4D BIM with VR to enhance students' understanding of project planning, scheduling, and error detection. Through a comparative analysis of 2D drawings and VR-based simulations, this research quantitatively measures performance improvements in error detection and sequencing comprehension, filling a notable gap in the literature. Additionally, the study offers new insights into the application of 4D-BIM VR simulations in construction management education, emphasizing practical, hands-on learning experiences that align directly with the skills required in the construction industry. By providing detailed empirical data and a comprehensive analysis, this research underscores the unique benefits and challenges of integrating 4D BIM and VR technologies into construction management curricula, offering valuable recommendations for further curriculum enhancement and technological integration.

3. Materials and Methods

Based on the research question and the goal of exploring the impact of immersive learning and virtual reality on learning outcomes and student engagement in construction management education, an explanatory sequential design would be the most appropriate approach. This approach is particularly suitable due to its capacity to facilitate a systematic progression from the collection and analysis of quantitative data to the subsequent collection and analysis of qualitative data [35,36]. The systematic progression from quantitative to qualitative data collection is crucial, as it establishes statistical relationships and patterns, providing a quantitative understanding of the phenomenon under study. The subsequent qualitative phase adds depth and nuanced insights to the quantitative findings, helping to explain and interpret the quantitative results in a more comprehensive manner, enhancing the validity and reliability of the research findings.

To achieve the aim of this study, two distinct experiments were administered to undergraduate construction management students at the United Arab Emirates University (UAEU), as detailed in Section 3.1. A questionnaire was distributed among the participants after each experiment, as elaborated in Section 3.3. Quantitative and qualitative questionnaire data were analyzed using exported tables and Excel graphs. Figure 1 shows the workflow of the adopted methodology.

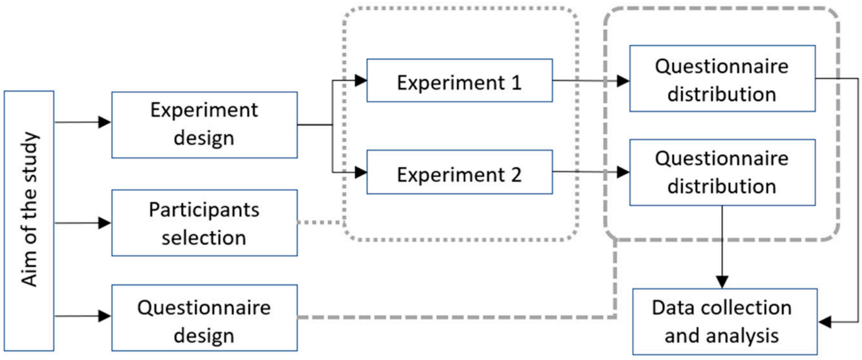


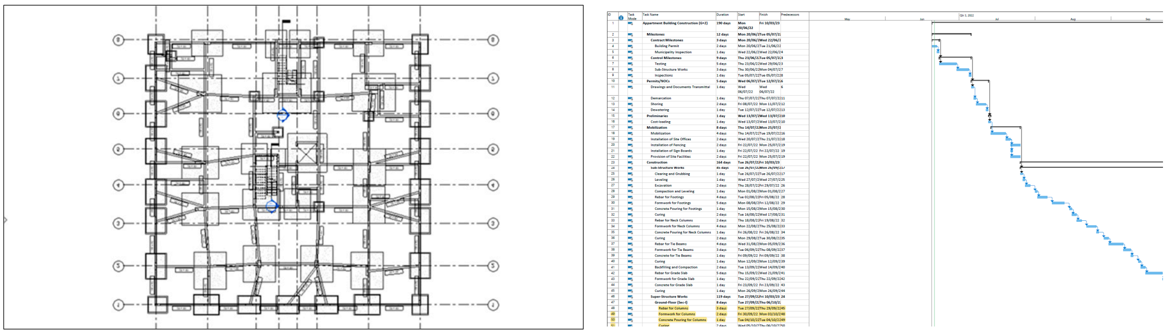
Figure 1. Methodology workflow.

3.1. Experiment Design

This study conducted two distinct experiments with a sample of undergraduate construction management students in the VR laboratory at the United Arab Emirates University (UAEU) in the city of Al Ain. The first experiment utilized traditional 2D drawings, while the second experiment employed a BIM-based VR simulation environment with preprogrammed scenes. Intentional errors were added to both experiments, categorized into the design, construction sequence, and safety errors, and added to different scales and levels. The experiments with 2D drawings containing deliberate errors aimed to assess students' ability to detect these errors using traditional methods and provide insights into how students interacted with and understood construction sequences presented in 2D format, highlighting any challenges or limitations in this approach. These steps were repeated in a second experiment with VR and preprogrammed scenes, focusing on evaluating students' responses to errors and their engagement in a simulated construction environment, thereby exploring the potential benefits and challenges of immersive learning technologies in enhancing learning outcomes.

3.1.1. First Experiment

Participants were presented with 2D views of a BIM model depicting a multi-story concrete frame building, developed using Autodesk Revit 2023© [37], and a pdf list of construction activities created in Autodesk Navisworks Manage 2022. The BIM model was prepared beforehand and presented in 2D views for various floor plans at different levels containing main structural components, as illustrated in Figure 2a,b, respectively. The 2D drawings and the Gantt chart were used to simulate common scheduling errors such as the incorrect sequencing of tasks, missing activities, and overlapping activities. These errors were intentionally introduced to mimic real-world challenges that can arise in construction project management. For instance, a task that should logically follow another might be placed out of order, leading to potential delays and resource conflicts. By identifying these errors, students learn to connect the visual representation of the building components with the sequence of construction activities, improving their understanding of project scheduling. Students participated in a 5 min orientation session before the commencement of the tests. Students received detailed instructions, information, and requirements during this session, including the test's purpose. They had the opportunity to ask any questions before the test began. Each student had a maximum of 30 min for this experiment.



(**a**) (**b**)

Figure 2. (**a**) Construction drawings depicted in the traditional 2D method in Revit © software; (**b**) information on construction activities extracted as a PDF file from Autodesk Navisworks Manage.

3.1.2. Second Experiment

In the second experiment, we constructed a 4D simulation of the main structural components of the sample project used in the first experiment. This simulation was employed in a VR environment to visualize the sequencing of construction activities in 3D using a VR headset. Pre-programmed scenes were created in IVEs for students to experience the same project, aiming to assess their comprehension of the construction activities sequence. Each student had a maximum of 30 min for this experiment. The rationale behind this choice was to provide an immersive and interactive learning experience that closely mirrored real-world construction scenarios, enhancing students' ability to understand and manage construction sequences. This approach also evaluated whether experiencing errors in a dynamic, immersive environment would improve students' problem-solving skills and adaptability. To control the study and ensure consistency, the same set of pre-programmed scenes and errors were used for all participants. The test team closely monitored the sessions to assist with navigation and provide guidance. The test team observed and assisted participants in the IVE to help with the navigation. Students were allowed to navigate freely around the building at all levels. Through navigation, students could see the construction sequencing of listed activities in pre-arranged scenes from all angles. Guidance and needed information were provided to the users at each phase to help in understanding the sequence of the test. The simulation included phases from laying out the foundations through framing and finishing the building frame step by step, with the same errors as the first test. Figure 3 shows all scenes' setup of the test simulation in Revit © 2023.

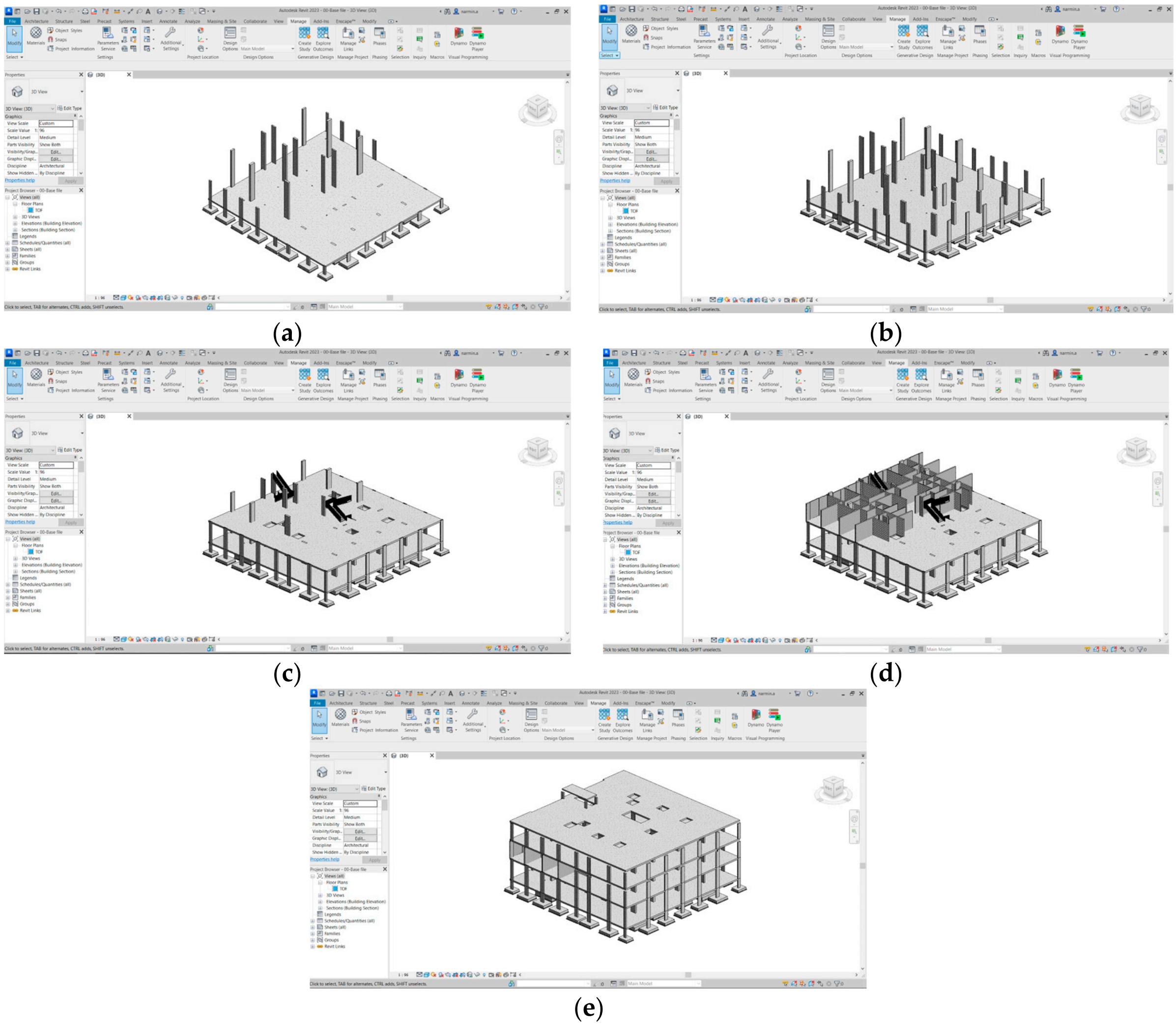


Figure 3. Five pre-arranged scenes in Autodesk Revit of the construction sequence, which were exported for the VR-based test. (**a**) Scene 1; (**b**) scene 2; (**c**) scene 3; (**d**) scene 4; (**e**) scene 5.

3.1.3. Model Creation, VR Setup and Monitoring

Autodesk Revit © 2023 was used to create the model of a multi-story concrete frame building, initially to be used as 2D drawings for the first experiment and later as a 4D-BIM model for the second experiment. The second experiment accessed the model through the preinstalled plug-in tool, Enscape^{TM} 2022, version 3.3. [38], transforming this 4D-BIM model into an immersive virtual environment (IVE). The chosen VR system was the Oculus headset, known for its lightweight design that allows users to immerse themselves in the virtual environment and move freely within it. The Oculus tracking system enabled users to navigate as if in the real world, adjusting the view in the headset based on their movements. Moreover, the system included a controller that users used to control the scene while immersed in IVE [39]. The experiment team utilized a smart board to monitor students' movements in VR. This involved linking the laptop to a large smart screen, allowing the team to observe the 4D-BIM model's sequencing of construction activities displayed in the VR glasses worn by the students, as illustrated in Figure 4.

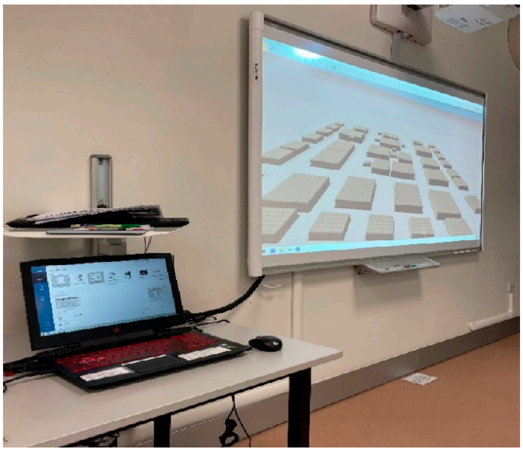


Figure 4. The second experiment is linked with an intelligent screen and monitored by the experiment team.

3.2. Participant Sampling

The participants in this study were selected using a combination of recruitment methods to ensure a diverse yet relevant sample group. The participants in this study were required to have completed at least one construction management course during their undergraduate studies to ensure basic knowledge and familiarity with construction processes and terminology. This prerequisite was essential for both experiments, which involved tasks and assessments related to construction sequencing, error detection, and an understanding of construction activities. By including participants with prior exposure to construction management coursework, the study aimed to gather data from individuals with a foundational understanding of the subject matter, thereby enhancing the reliability and relevance of the findings.

The recruitment process involved sending out emails to potential participants, seeking referrals from faculty members or peers, and directly contacting students who met the inclusion criteria. This approach aimed to gather a sample representing a range of experiences and perspectives within the target population of undergraduate construction management students. The sample consisted of 38 individuals aged between 18 and 23 years, all of whom had successfully completed at least one construction management course during their undergraduate studies. While the sample size provided valuable insights, its small scale may limit the generalizability of the findings to a broader population of construction management students. Future research with a larger and more diverse sample would be beneficial to strengthen the external validity of the study's conclusions.

All participants provided informed consent, and ethical considerations were rigorously addressed throughout the study. The recruitment strategy and informed consent process were thoroughly documented to ensure the transparency and replicability of the research methodology.

After completing the experiments, students were asked to complete a post-questionnaire to provide quantitative and qualitative data on their performance and engagement during the experiments. Students completed the survey twice, once for each experiment, and their responses were evaluated separately for each experiment. Afterward, a feedback form was recorded to test whether VR learning affects students' learning, understanding of construction sequences, and how to construct a concrete frame building.

Quantitative data were collected through structured assessments and survey questionnaires designed to measure participants' ability to detect errors and understand construction sequencing in both a 2D drawing format and VR. The structured nature of these assessments ensures consistency in evaluation across participants. It allows for objectively measuring factors such as error detection and the comprehension of construction sequencing as targeted learning outcomes. The assessments focused on objective measures of performance and comprehension within both experiments. Qualitative data were gathered through open-ended questions in the same survey questionnaire and observational notes by the experiment team during both sessions. This qualitative approach aimed to capture the participants' subjective experiences, perceptions, and challenges encountered in VR and 2D drawing formats. Thematic analysis and content analysis were employed to identify patterns, themes, and emerging insights from the qualitative data. The qualitative approach is essential in the explanatory sequential mixed-method design because it provides a rich, detailed understanding of the research phenomenon and informs the development of the quantitative phase [36].

These data were analyzed to determine the impact of immersive learning and virtual reality on learning outcomes and engagement of the participants. The quantitative and qualitative data were integrated to comprehensively assess the experience of VR-based learning and traditional 2D drawing formats. The quantitative data provided objective performance measures, while the qualitative data offered deeper insights into the participants' engagement, perceptions, and challenges. The triangulation of data sources enhanced the validity and reliability of the study's findings, contributing to a nuanced understanding of the impact of VR simulations on construction engineering education.

3.3. Development of Survey Questionnaire

In this study, various themes were investigated, covering aspects such as measurement challenges, information clarity, error detection, methodology effectiveness, familiarity, and areas needing further clarification. These themes were explored through a survey questionnaire divided into different sections. The first part of the survey comprised demographic questions aimed at gaining insights into the participants' status, study year, construction management-related coursework, and internships in the construction field. Following this, questions were asked about participants' familiarity and experience with the Gantt chart (traditionally used as a tool for teaching construction-related activities), VR, and construction planning. A crucial aspect of the survey focused on assessing the tool or technique used in the experiment, using a Likert scale with five sub-questions. These sub-questions were designed to gauge participants' engagement, clarity and understanding of information, need for consulting with the experiment team for clarifications, effectiveness in presenting construction sequencing information, and ease of detecting sequencing errors/irregularities, as shown in Table 1.

Table 1. The 5-point Likert scale questions.

Likert-Scale Questions	Measured Aspects
Information was clear with this method.	Method functionality
Information was easily understood with this method	Information delivery
Required the need to consult with the experiment team for clarifications	Content
The method was effective in presenting the construction sequencing information.	Method presentation
Sequencing errors/irregularities were easy to locate.	Engagement

As mentioned, this post-experiment survey questionnaire was also used to gather qualitative data. This was achieved through the inclusion of open-ended questions. Students were asked about their experiences during the experiments, including their perceptions of the technologies used, their understanding of the errors in the experiments, and their levels of engagement. The qualitative data collected provide insights into how and why immersive learning and virtual reality impact learning outcomes and engagement in construction management education. This qualitative data also helped to explain any unexpected or contradictory results from the quantitative phase. Integrating the quantitative and qualitative data provided a comprehensive understanding of the research problem and a more accurate representation of the findings. It also helped to validate and complement each method's findings, thus reducing the limitations of each approach when used separately. Thus, the combination of quantitative and qualitative data ensured the validity and accuracy of the research results.

3.4. Ethical Considerations

As described previously, this study considered several ethical considerations, including informed consent: Participants were fully informed about the research objectives, procedures, and benefits, and they had the right to decline or withdraw from participation at any time. Participants' personal information, such as names and contact details, was kept confidential. The data collected were also stored securely and anonymously.

4. Results

4.1. Two-Dimensional-Based Experiment Results

For the first 2D-based experiment, most students (47%, 18 students) reported it was moderately difficult, with 42% (16 students) indicating that it was not difficult, and 11% (4 students) agreed that 2D drawings and Gantt charts were complicated. Additionally, 44% (17 students) were unsure that they found all irregularities/incorrectness in the construction sequence. Figure 5 presents the outcomes of the five sub-questions measured on the Likert scale. Regarding questions about the clarity of information in this experiment, 52% (20 students) agreed that the information was clearly presented with this method, 21% (8 students) strongly agreed with the statement, 24% (9 students) were neutral, 3% (1 student) disagreed, and no students strongly disagreed. These results indicate a generally positive perception among participants regarding the clarity of information in the experiment, with a majority finding the information clear and comprehensible.

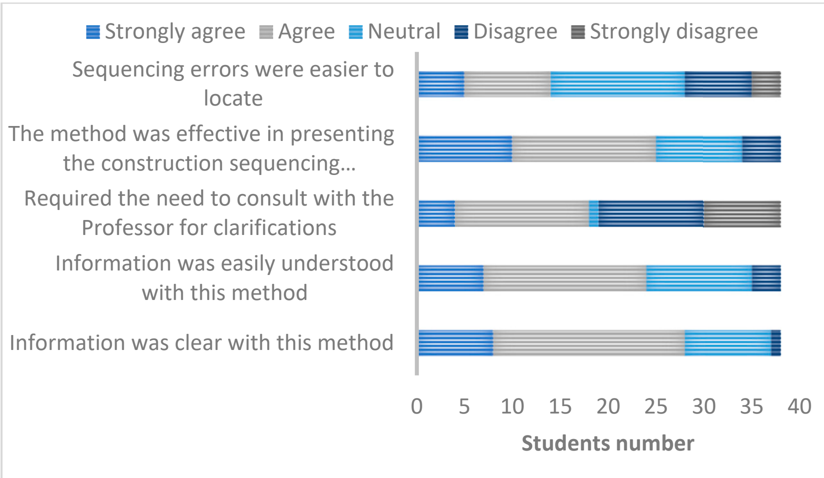


Figure 5. The 5-point Likert scale responses during the 2D-based experiment.

Regarding the Likert-scale question concerning the ease of understanding information, 45% (17 students) of students agreed that this method presented easily understood information, 29% (11 students) were neutral towards the statement, 18% (7 students) strongly agreed, and 8% (3 students) disagreed. However, almost half of the students (48%, 18) agreed and strongly agreed that they "did not require the need to consult with the experiment team for clarifications". For the fourth Likert scale question regarding how effective this method was in presenting the construction sequencing information, 40% (15 students) agreed with the statement, 26% (10 students) strongly agreed, 24% (9 students) were neutral regarding the statement, and 11% (4 students) disagreed. Regarding the final question on how easily the errors are located, 37% (14 students) found it neutral, 24% (9 students) agreed with the statement, 18% (7 students) disagreed, 13% (5 students) strongly agreed, and only 8% (3 students) strongly disagreed. The questions and the responses are shown in Figure 5. Overall, 60% of students (23 students) found the traditional 2D-based approach effective or highly effective in understanding construction sequences, while 40% (15 students) were either neutral or found it ineffective. This underscores a significant portion of students facing challenges with the traditional method, emphasizing the need for alternative instructional approaches.

4.2. Four-Dimensional-BIM VR-Based Experiment Results

Regarding the 4D-BIM VR-based experiment, most students (55.3%, 21 students) were already familiar with VR technology, while 15.8% (6 students) had no experience with VR. Additionally, 28.9% (11 students) were not only familiar with VR but also had previous hands-on experience with VR. Following the VR orientation, all participants navigated smoothly within the VR-based experiment. Most (62%, 24 students) strongly agreed that the VR test posed no significant challenge. These findings were further validated by observations from the experiment team, who noted that students engaged freely and comfortably within the VR environment, adjusting to their own pace. This suggests a positive trend in the application of VR in education, indicating a growing acceptance and integration of VR as a tool for learning and engagement among students.

Regarding the sequencing errors, 61% (23 students) of respondents believed they identified all irregularities/incorrectness in the construction sequence using this 4D-BIM VR-based approach. This indicates a high level of confidence among participants in effectively detecting and addressing sequencing errors within the virtual reality (VR) environment, underscoring the method's efficacy in enhancing students' comprehension of construction sequencing.

Figure 6 presents the outcomes of the five sub-questions measured on the Likert scale. In questions concerning information clarity within this experiment, 61% (23 students) of participants strongly agreed, and 34% (13 students) agreed. Only 5% (2 students) found the VR method neutral regarding clarity, with no responses indicating disagreement or strong disagreement with the statement. Regarding the Likert-scale question concerning the ease of understanding information, 55% (21 students) of participants strongly agreed that the VR experiment was easily understandable, 34% (13 students) agreed, and 11% (4 students) had a neutral perspective. These responses underscore the overwhelmingly positive perception among students regarding the clarity and ease of understanding of information in the VR-based approach, highlighting its effectiveness in conveying information comprehensively and with ease of comprehension.

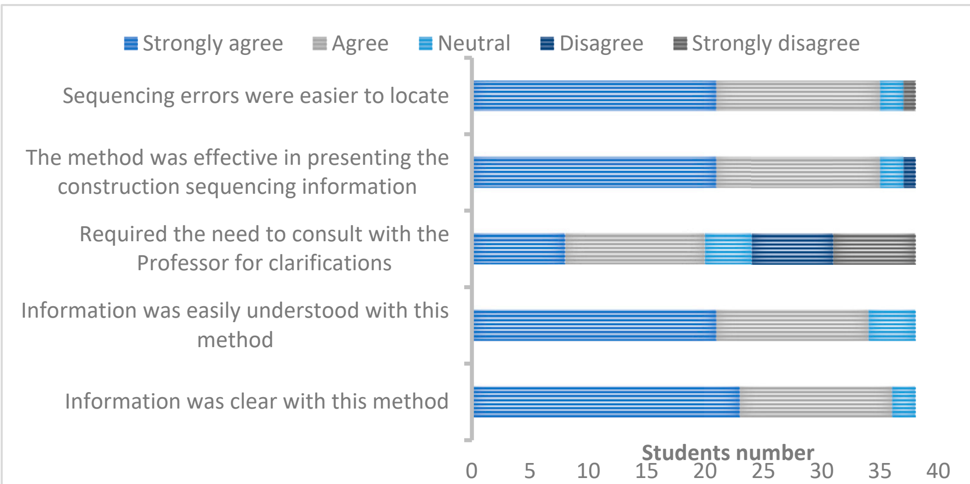


Figure 6. The 5-point Likert scale responses during the VR-based experiment.

Regarding the need for clarification assistance, 21% (8 students) of participants strongly agreed, and 32% (12 students) agreed that they required clarifications from the experiment team. On the other hand, 18% (7 students) disagreed, 18% (7 students) strongly disagreed, and 11% (4 students) expressed a neutral stance. This indicates that a notable percentage of participants sought additional clarifications during the experiment, underscoring the importance of addressing potential points of confusion or complexity, whether related to the use of technology or the specific processes within the VR environment.

Regarding the method's effectiveness in presenting the construction sequencing information, 55% (21 students) of students strongly agreed with the statement, 37% (14 students) agreed, and only 8% (3 students) were neutral or disagreed. This indicates a high consensus among students regarding the 4D-BIM VR-based approach's success in conveying construction sequencing information, highlighting its efficacy and clarity. Possible reasons contributing to this success may include the immersive nature of the VR environment, the interactive features that engage students, and the visual representation that aids in understanding complex sequences.

The results regarding the ease of finding sequence errors mirrored the effectiveness of presenting construction sequencing information. Specifically, 55% (21 students) of students strongly agreed with the statement, 37% (14 students) agreed, and only 8% (3 students) were neutral or disagreed. This indicates a high level of agreement among participants regarding the effectiveness of the 4D-BIM VR-based approach in presenting construction sequencing information and facilitating the detection of sequence errors during the experiment.

The quantitative data show that the 4D-BIM VR-based approach resulted in a 27% increase in students' ability to detect errors compared to the 2D-based method. This significant improvement highlights the potential of VR technology to enhance students' skills in identifying and correcting construction sequence issues.

4.3. Error Detection in Both Experiments

For the open-response questions and comments, many students reported that the VR–based simulation learning method was more effective and understandable than the traditional test that depended on 2D drawings and schedules. On the one hand, for one of the questions measuring difficulty aspects in both experiments, "What aspects were difficult for you to complete this task? Please comment ..". Students answered in terms of 2D-based drawing, with the following responses: "There are too many steps, many tasks to notice the errors", "hard to understand and visualize the steps", and "correlate the Gantt chart to the 2D drawings". On the other hand, the following answers were given in the VR-based experiments: "The gear usage", "exploration of how to use VR as a tool"; "controlling the VR tools", and "at first there were difficulties navigating the POV but eventually learned". For another question, "What could be done to make it easier for you to perform this task?". Students answered, regarding the first task, with "the building was not complex and required many tasks", "Show a graph to state the activity sequence and independence" and "Provide pictures supporting the task sequence". However, for the second task, the answers were "Could be better to add 2D and 3D in VR to check the difference and the not clear idea", "It was an easy task and easier to notice the mistakes".

For error detection, the experiment team noticed that students found more errors in VR-based experiments than in the traditional method. However, they also found irrelative errors in the sequence, like openings and structure design errors, which indicate users' cognition in the VR environment. Further, some students could not relate to the model scale in VR, as they navigated around the model with no specific scale to use as a reference. On the contrary, in the 2D method, students could read the drawings in terms of scale and representation meaning, but the sequence was not evident in the Gantt chart for "many tasks that made it hard to track", as one of the students said.

After the two experiments, students were asked to write down any comments or feedback. Most of the students agreed that the information given in the IVE is "self-explanatory" without further clarification from the experiment team. The comments primarily focused on comparing the VR experience with the traditional 2D method. For example, "It was easier than the Gantt chart", "It was really easy to understand with VR" and "in VR task is clear and easy", "VR was enough". Some students found VR navigation enjoyable, and felt that learning more about constructing a building modelwas easy. However, a number of students (23%) reported feeling motion sickness and dizziness while navigating around the model in the virtual environment, as shown in Figure 7. The VR-based approach improved error detection rates and significantly reduced the time required for students to complete tasks compared to the 2D-based method. On average, students completed the VR tasks 35% faster, indicating an increased efficiency and better engagement with the material.

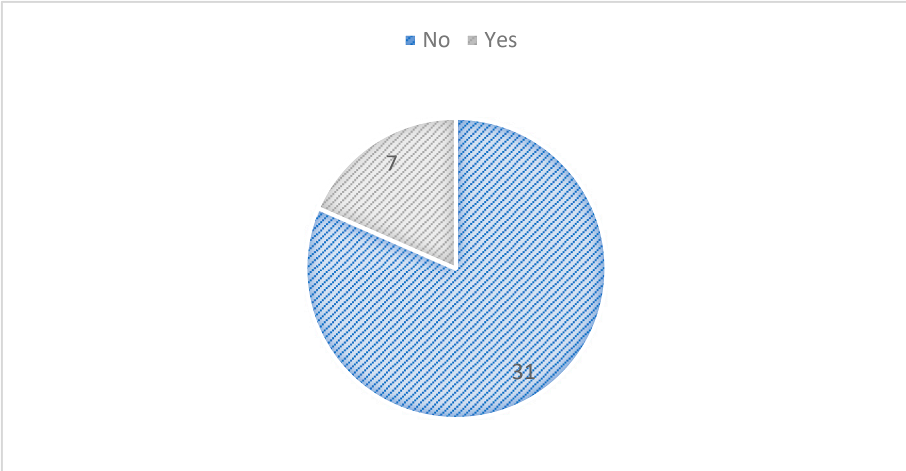


Figure 7. Motion sickness in the VR-based experiment.

Overall, the results provide a comprehensive view of the student's experiences and performances during the experiments. These results indicate that VR-based learning environments may enhance students' understanding and engagement in construction management education, suggesting potential benefits of integrating such technology into educational practices.

5. Discussion

This study's findings shed light on how VR technology is used in education and offer insights into its potential advantages and difficulties. Notably, the research uncovered several significant results using the 5-point Likert scale that provide a more nuanced picture of students' experiences and views of VR technology in construction instruction.

While more than 50 percent of the students found the 2D drawings and sequencing clear, effective, and easily understandable, the goal of integrating 4D BIM and VR into construction management education extends beyond basic comprehension. The primary purpose of utilizing 4D BIM in education is to enhance the depth and breadth of students' understanding of complex construction processes, which are often challenging to visualize and grasp through traditional 2D drawings alone. Four-dimensional BIM integrates time-related information with 3D models, enhancing the visualization and comprehension of construction sequences. This dynamic understanding improves problem-solving skills by allowing students to resolve conflicts preemptively and offers a realistic, interactive learning experience that simulates real-world scenarios. Such immersive learning environments prepare students for industry practices, aligning their skills with modern construction challenges. The positive feedback from 75% of students on the VR experience underscores its effectiveness in making learning engaging and impactful, fostering deeper comprehension and better professional readiness. These findings align with other studies on the benefits of VR in construction education [12,29].

Moreover, VR technology holds promise beyond scheduling in construction education. Safety training is a critical application where VR can immerse students in hazardous scenarios without real-world risks, allowing them to practice safety protocols and emergency responses. Site management is another area where VR simulations can train students in overseeing construction progress, logistics, and resource allocation in a controlled environment. These applications extend the educational scope of VR beyond theoretical learning to practical, hands-on training that prepares students for diverse roles in construction management.

5.1. Construction Sequence Errors and Engagement

The study revealed that the VR environment helped students clearly understand the sequence, reducing construction sequence errors and increasing student engagement. However, it also highlighted that students were not always able to correctly identify all mistakes, as they lacked the comprehensive building knowledge to do so accurately. This underscores the importance of strategies to bridge knowledge gaps and align students' understanding with the traditional teaching approach.

These findings underscore the versatile nature of VR technology in construction education. While it offers customization, spatial awareness, and engagement benefits, it also presents technological challenges and underscores the importance of students' prior knowledge and experience. This study emphasizes the necessity of establishing comprehensive frameworks for VR integration, building upon existing research highlighting VR's potential for enhancing students' skills and knowledge in construction education. Further research is needed to explore different VR software alternatives, improve VR hardware ergonomics, and develop strategies to integrate VR technology effectively within the existing curriculum. These steps will help maximize the educational benefits of VR and prepare students for the evolving demands of the construction industry.

5.2. Method Functionality and Spatial Understanding

The VR environment's ability to initiate with a 1:1 model scale and a predefined starting position was observed to reduce cognitive errors related to model scale comprehension. Additionally, providing the entire model upfront before commencing the assembly sequence could enhance students' spatial understanding and improve information retention. The VR environment's feature that lets students control their movement and adjust sequence speed also made better information retention possible.

However, the study also identified some technical challenges, including blurriness and low resolution. The specific VR program (Enscape) utilized to create the setting may have impacted these difficulties. This implies that investigating different VR software alternatives may result in a better depiction of the sequences and a more pleasant user experience. Notably, some students reported discomfort while using the VR gear, underscoring the necessity of ensuring a comfortable and user-friendly VR experience by implementing ergonomic design principles and providing adequate training on VR equipment usage. The weight of VR headsets was another issue reported by some students. This emphasizes the importance of continually improving VR gear for enhanced usability and to maximize its educational benefits.

5.3. Impact of Prior VR Experience

The study revealed interesting insights into how students' prior experience with VR technology influenced their perception and engagement with the VR experiment. Those with prior experience seemed to approach the VR world differently, possibly due to their familiarity with navigating virtual environments and interacting with VR tools and interfaces. This prior expertise seems to have shaped their expectations, confidence levels, and overall comfort with VR technology. In contrast, students without prior experience approached the VR experiment with curiosity and apprehension, needing more time to acclimate to the virtual environment. Their initial unfamiliarity led to a steeper learning curve but also provided a fresh perspective on the intuitive usability and accessibility of VR technology. Despite initial challenges, these students demonstrated significant adaptability and learning, indicating the potential for VR to be an effective educational tool, even for those new to the technology.

5.4. Customized Learning Environment

The study highlighted that the VR environment, with its tailored setup, facilitated easy interaction for students within the VR simulation. This customizable aspect suggests significant potential for enhancing the educational experience. By allowing students to engage with the content in a more intuitive and personalized manner, VR technology opens avenues for deeper comprehension, increased engagement, and more effective retention of knowledge. Customizing the VR environment to fit specific educational needs demonstrates its adaptability and potential for personalized learning.

6. Conclusions

This study investigated whether 4D-BIM VR-based simulations could effectively teach construction engineering. The study used a mixed-method approach with qualitative and quantitative data collection methods. The participants were given two tests, one illustrated with 2D drawings and another in a VR simulation environment, to assess their ability to detect intentional errors in project program planning and scheduling. The results of this study suggest that VR simulations have the potential to be used as an effective tool in construction engineering education. The quantitative data showed that the participants were more likely to detect VR environment errors than the 2D drawings and understand the construction sequencing better. The qualitative data revealed that the students responded positively to the VR experience, finding it engaging and informative. However, the study also identified areas for improvement regarding the quality of the IVE in the context of students' training. Further continuous improvement and integration of VR simulations in the construction curriculum are recommended to enhance the learning and teaching experience. Future studies should focus on measuring augmented skills resulting from immersive virtual environments and exploring their effect on refining students' critical thinking and problem-solving abilities. A larger sample size is also recommended for more feedback on enhancing the VR experience. Future research could explore integrating these technologies across various construction management topics. Finally, this study has provided valuable insights into the potential of VR simulations in construction engineering education. It lays a foundation for further research and exploring the limitations of using VR simulations in construction engineering education. The study contributes novel insights by demonstrating how VR simulations can enhance construction engineering education through improved error detection and sequencing comprehension. While acknowledging related works, this research uniquely emphasizes the ongoing need to refine and expand VR integration in educational settings to fully exploit its benefits. These findings lay the groundwork for future research, offering a foundational framework to maximize the educational potential of VR simulations in construction engineering.

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